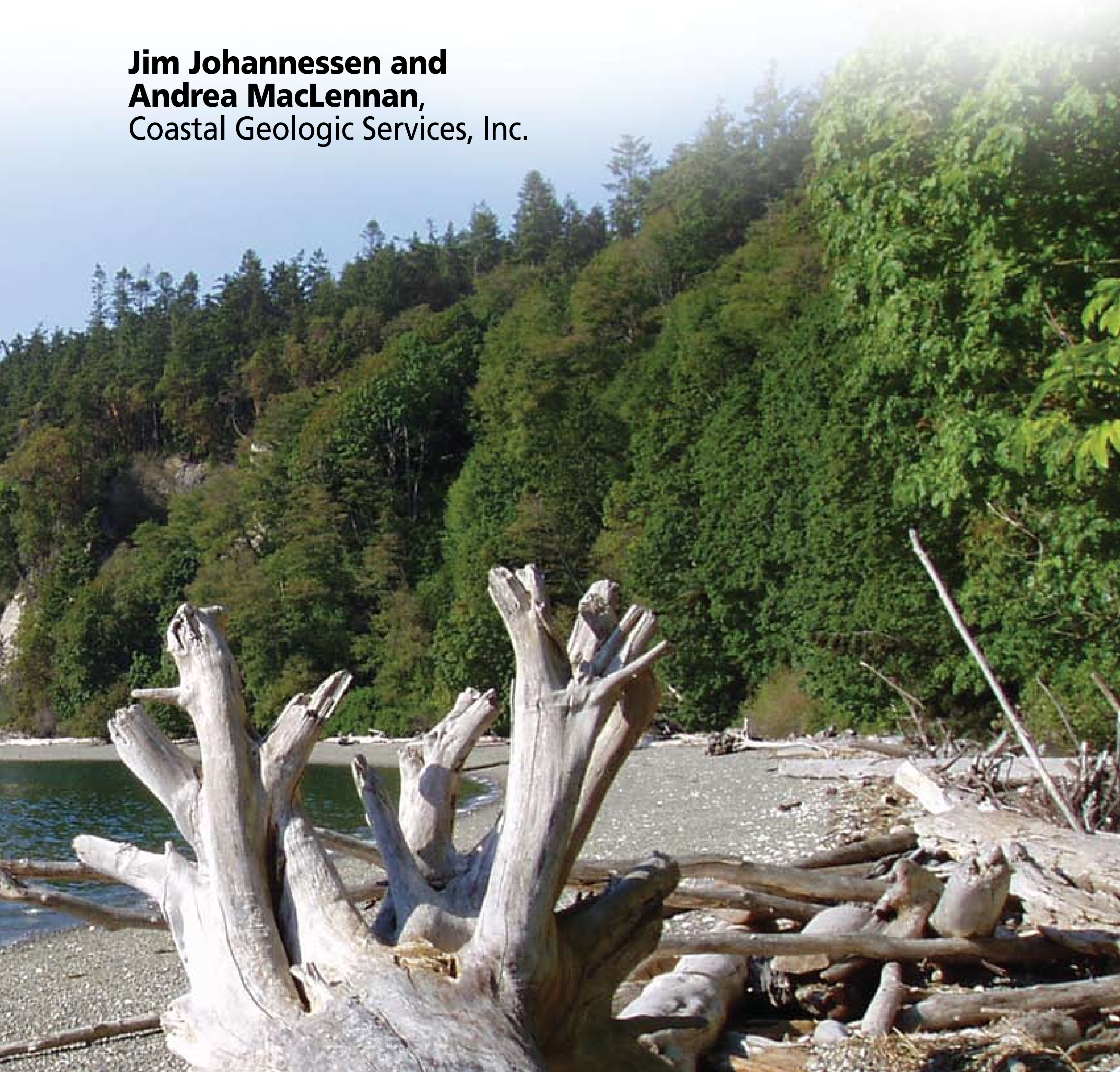
Technical Report 2007-04

Beaches and Bluffs of Puget Sound

Prepared in support of the Puget Sound Nearshore Partnership

Jim Johannessen and
Andrea MacLennan,
Coastal Geologic Services, Inc.



Valued Ecosystem Components Report Series

PUGET SOUND
NEARSHORE
PARTNERSHIP

RESTORING OUR
ECOSYSTEM HEALTH

The Puget Sound Nearshore Partnership (PSNP) has developed a list of valued ecosystem components (VECs). The list of VECs is meant to represent a cross-section of organisms and physical structures that occupy and interact with the physical processes found in the nearshore. The VECs will help PSNP frame the symptoms of declining Puget Sound nearshore ecosystem integrity, explain how ecosystem processes are linked to ecosystem outputs, and describe the potential benefits of proposed actions in terms that make sense to the broader community. A series of "white papers" was developed that describes each of the VECs. Following is the list of published papers in the series. All papers are available at *www.pugetsoundnearshore.org.*

Brennan, J.S. 2007. Marine Riparian Vegetation Communities of Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-02. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Buchanan, J.B. 2006. Nearshore Birds in Puget Sound. Puget Sound Nearshore Partnership Report No. 2006-05. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Dethier, M.N. 2006. Native Shellfish in Nearshore Ecosystems of Puget Sound. Puget Sound Nearshore Partnership Report No. 2006-04. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Eissinger, A.M. 2007. Great Blue Herons in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-06. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Fresh, K.L. 2006. Juvenile Pacific Salmon in Puget Sound. Puget Sound Nearshore Partnership Report No. 2006-06. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Johannessen, J. and A. MacLennan. 2007. Beaches and Bluffs of Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-04. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Kriete, B. 2007. Orcas in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-01. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Leschine, T.M. and A.W. Petersen. 2007. Valuing Puget Sound's Valued Ecosystem Components. Puget Sound Nearshore Partnership Report No. 2007-07. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Mumford, T.F. 2007. Kelp and Eelgrass in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-05. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Penttila, D. 2007. Marine Forage Fishes in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-03. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Front and back covers: Whidbey Island (courtesy of Washington Sea Grant)

Contents

Acknowledgments

Drafts of this paper were improved by comments from Maurice Schwartz, Western Washington University; Hugh Shipman, Washington Department of Ecology; Guy Gelfenbaum, U.S. Geological Service; Jan Newton, University of Washington (UW); and Megan Dethier, UW-Friday Harbor Laboratory. Some data summaries were prepared by Bill Schenken. Thanks to Megan Dethier for coordination. In memory of Matt Chase of Coastal Geologic Services Inc.

Recommended bibliographical citation:

Johannessen, J. and A. MacLennan. 2007. Beaches and Bluffs of Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-04. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Available at *www.pugetsoundnearshore.org.*

The Puget Sound Nearshore Partnership Steering Committee initiated the concept of this paper and the others in this series. The Nearshore Partnership Project Management Team (PMT) – Tim Smith, Bernie Hargrave, Curtis Tanner and Fred Goetz – oversaw production of the papers. The Nearshore Science Team (NST) played a number of roles: they helped develop conceptual models for each valued ecosystem component (VEC), in collaboration with the authors; individual members were reviewers for selected papers; and members were also authors, including Megan Dethier, Tom Mumford, Tom Leschine and Kurt Fresh. Other NST members involved were Si Simenstad, Hugh Shipman, Doug Myers, Miles Logsdon, Randy Shuman, Curtis Tanner and Fred Goetz.

The Nearshore Partnership organization is especially grateful for the work done by series science editor Megan Dethier, who acted as facilitator and coach for the authors and liaison with the NST and PMT. We also thank the U.S. Army Corps of Engineers Public Affairs Staff — Patricia Grasser, Dick Devlin, Nola Leyde, Casondra Brewster and Kayla Overton — who, with Kendra Nettleton, assisted with publication of all the papers in the series.

Finally, the Nearshore Partnership would like to thank the Washington Sea Grant Communications Office — Marcus Duke, David Gordon, Robyn Ricks and Dan Williams — for providing the crucial editing, design and production services that made final publication of these papers possible.

This report was supported by the Puget Sound Nearshore Ecosystem Restoration Project through the U.S. Army Corps of Engineers and Washington Department of Fish and Wildlife.

For further information or printed copies of this report, contact Curtis Tanner, Local Project Manager, Puget Sound Nearshore Ecosystem Restoration Project, Washington Department of Fish and Wildlife, 600 Capital Way North, Olympia, Washington 98501-1091.
curtis_tanner@fws.gov.

Executive Summary

The shores of the Puget Sound region provide valuable recreational and economic benefits for the burgeoning population. Beaches and bluffs of the Puget Sound region provide critical nearshore habitat functions and values for the region's fish and wildlife. Coastal bluffs are the primary source of beach sediment along the Puget Sound shore, and their natural erosion is essential for maintaining beaches and associated nearshore habitats. Critical habitats dependent on functioning coastal systems include coastal forests, spawning beaches for forage fish (such as surf smelt), eelgrass beds, and salt marshes, all of which shape the health of salmon populations.

Puget Sound and the Northern Straits encompass the central feature in the Puget Lowland, consisting of a complex series of deep, generally north-south-trending basins. Puget Sound was created by the repeated advance and retreat of glacial ice sheets, the most recent of which advanced between 15,000 and 13,000 years ago (Booth 1994). The area's glacial legacy has resulted in abundant steep bluffs (sometimes referred to as sea cliffs, although locally termed bluffs) of up to 400 feet in elevation, which are both dramatic and dynamic features.

The shores of Puget Sound are highly convoluted, encompassing approximately 2,380 miles of shore length (Washington State Department of Natural Resources (WDNR) 2001). Extensive sand and gravel beaches provide a wide variety of coastal configurations that in turn serve as habitat links between rivers and the marine environment for salmon and the many interdependent species of the Puget Sound region.

The general shore types found throughout the region include rocky coasts, coastal bluffs, bluff-backed beaches, depositional beaches, deltaic shores, and spits associated with protected lagoons and salt marshes. The most prevalent of these shore types are bluff-backed beaches: coastal bluffs fronted by narrow mixed sand and gravel beaches. However, excluding spits and other types of depositional beaches, most Puget Sound area beaches are only a thin veneer of sediment atop a relatively flat erosional platform (Shipman 1995), and are therefore subject to erosion when conditions are altered due to human-induced change.

Bluff erosion is caused by marine, subaerial and human-induced erosion, often in concert. Waves caused by windstorms typically drive bluff erosion over the long term. Wave attack interacts with locally variable bluff geology and aspect, toe protection and other factors, including management practices. Precipitation frequently triggers landslides at over-steepened bluffs (Tubbs 1974). Coastal bluffs are the primary source of sediment for most Puget Sound beaches (Keuler 1988), such that bulkheads and other shore modifications that limit bluff erosion and coastal sediment transport have led to major changes in sediment supply and associated changes in beach and habitat stability.

Cumulatively, more than 805 miles, or 34 percent, of the Puget Sound and Northern Straits shore has been modified (WDNR 2001). Bulkheads and other shore-parallel structures along coastal bluffs impound potential beach sediment, commonly bury upper beach spawning habitat and fundamentally alter the beach and backshore, resulting in a decrease in the amount of drift sediment available for maintenance of down-drift beaches. Burial of the backshore results in reduced beach width (Griggs 2005) and loss of habitat area. The remaining upper beach typically suffers from changed hydraulic conditions. Although research has been very limited locally, bulkheads are thought to cause some degree of localized beach erosion (MacDonald et al. 1994). As a result of these changes, beaches become more coarse-grained and gravel-dominant, which does not provide the same quality of habitat as a finer grained beach (Thom et al. 1994, MacDonald et al. 1994). Cross-shore structures, such as groins and jetties, also impact coastal processes by impeding sediment transport alongshore. This often results in sediment accumulating up-drift of the structure and erosion along the down-drift shore. Other common shore modifications in the Puget Sound nearshore include causeways, fill and dredge areas, mine and quarry areas, and overwater structures.

Sea level rise (SLR) and the impacts of global climate change are currently bringing accelerated change to the region's beaches and bluffs, with increased erosion rates and coastal flooding, heightening the need for new long-range planning efforts. Spatial variability in Puget Sound tectonics processes produces different rates of sea level rise across the region, referred to as relative sea level rise. Relative sea level rise in north Puget Sound is close to the global average, and is up to double the average in south Puget Sound (Snover et al. 2005).

Sea level rise will result in the landward migration of the shoreline, a response to the changes in the elevation of breaking waves on the beach profile. At unprotected shores, the response is generally a self-regulating process, as additional (eroded) sediment from the backshore or bluffs allows for down-drift shores to become higher and move landward, thereby maintaining the beach profile (Bray and Hooke 1997). Existing shore protection at beaches and bluffs will likely be less effective at preventing erosion with sea level rise, and the structures will likely incur damage due to increased water depths and greater wave energy and run-up. This would result in increased probability of structural damage, necessitating retreat or some form of repair (Bray and Hooke 1997). As a result, soft-shore protection is likely to be more effective at managing erosion control in the context of rising sea levels.

Coastal restoration that involves removing impairments to physical processes along Puget Sound area beaches and bluffs has begun to benefit nearshore habitats. This involves structure removal, repairing changes in estuarine function, and beach enhancement. Conservation of functioning areas and public education are also seen as key components of ecosystem recovery. A conceptual model for beaches and bluff restoration developed for this paper presents proposed restoration actions (management measures) and links these to restored natural processes, structural changes and anticipated functional responses. The model focuses on restoration of physical processes in order to improve the functioning of natural processes and habitats.

A number of significant data gaps exist in our understanding of Puget Sound beaches and bluffs, as we have not invested adequately in understanding fundamental coastal and bluff processes. Gaps in our knowledge and information include:

- Net shore-drift rates in the Puget Sound and Northern Straits;
- Historic shore changes, including using oral histories on undocumented changes such as beach mining;
- Quantitative sediment budgets;
- Long-term beach and bluff monitoring;
- Biological response to beach nourishment (response of beaches and surrounding habitats);
- The effects of climate change and sea level rise on the Puget Sound and Northern Straits shores.

This paper discusses beaches and beach processes, bluffs and bluff processes, and factors affecting these systems, including development, sea level rise and coastal restoration. The study area described is all of Puget Sound and the Northern Straits, from the mouth of the Elwha River on the northern Olympic Peninsula to the Whatcom County border with British Columbia, Canada. This paper is not intended to be a comprehensive review of these topics; instead it is a synthesis of existing knowledge and research that highlights the connections among issues and gaps in our knowledge. Existing sources with more depth include technical beach papers by Finlayson (2006) and Kirk (1980), a bluff paper by Shipman (2004), and a less technical book on local coasts by Downing (1983).

Preface

The beaches and bluffs of Puget Sound are, for many people, the reason that the region is an attractive place to live. Nationally, population growth is highest in coastal areas, and Puget Sound is no exception. Waterfront property, whether along high bluffs or on low, sandy spits, constitutes some of the highest-value real estate in the region. People who work in cities are often willing to travel great distances to live near the beach or to maintain vacation properties at the shore. Those who cannot live near the water are drawn in increasing numbers to public beaches and waterfront parks for beach walking, bird watching, tidepooling, and water sports. The use of beaches as children's playgrounds and "classrooms" is extremely popular. Commercial and recreational harvesting of shellfish and seaweed is widespread along Puget Sound's beaches.

Beaches and bluffs provide critical habitat for the region's fish and wildlife. Coastal bluffs are the primary source of beach sediment along the Puget Sound shore, and their natural erosion is critical for maintaining beaches and spits over the long term. Riparian vegetation growing on coastal bluffs and in the backshore shades the upper beach, provides large wood to the shoreline and contributes organic material to nearshore food webs (Brennan 2007). Beaches and associated habitats, such as eelgrass beds and salt marshes, serve as the linkage between rivers and the marine environment for migratory species such as salmon, and are important habitat for surf smelt, herring and other forage fishes (Fresh 2006, Mumford 2007, Pentilla 2007). Beaches are habitat for most of Puget Sound's shellfish (Dethier 2006). Beaches and bluffs are critical for feeding, roosting and, in some cases, nesting of a wide variety of marine and shorebirds (see Buchannan 2006, Eissinger 2007). Rocky shores, common in the northern part of the region, serve as habitats for other species, including kelps and many valued fishes.

A chronic problem is society's tendency to ignore the fact that beaches and bluffs are not static systems, and that interfering with their dynamic processes may have undesirable consequences. Human use of beaches and bluffs can jeopardize habitats and reduce the sustainability of the features. The construction of waterfront homes puts them in areas prone to natural hazards. Building houses on spits and beaches poses serious hazards from coastal flooding and storm damage and may cause increased erosion. Erosion control and diking associated with building near beaches can cause the destruction of salt marshes and backshore habitat. Constructing access roads to developments at beaches often restricts water flow into estuaries, altering habitats and aesthetic qualities. Building on bluffs can exacerbate landslide hazards due to loss of stabilizing vegetation and alteration of drainage patterns. Attempts to stabilize bluffs and reduce erosion through the construction of bulkheads and seawalls ultimately decreases the supply of sediment to nearby beaches, altering habitats and possibly shifting erosion problems to other shorelines. The cumulative impact of human modifications to the shoreline (currently one-third of Puget Sound's shoreline has been armored) may be far-reaching in terms of both habitat and existing human activities, particularly in the face of anticipated increases in the rate of sea level rise.

Puget Sound Beaches

Beach Morphology

A beach is an accumulation on the shore of generally loose, unconsolidated sediment that extends landward from the low water line to a definite change in material and form, such as to a bluff or dune. Beach sediment in the Puget Lowland ranges in size from very fine sand up to pebbles, cobbles, and occasionally boulders, often also containing shelly material. Puget Sound beaches commonly have two distinct foreshore components: the beachface, often called high-tide beach, and a low-tide terrace (Downing 1983). The high-tide beach consists of a relatively steep beachface with coarse sediment and an abrupt break in slope at its waterward extent (Figure 1). Low wave energy beaches are composed of poorly sorted sediment, with a relatively narrow backshore and intermittent intertidal vegetation. Higher wave energy beaches contain areas with well-sorted sediment over a broad intertidal and backshore area, usually devoid of fringing marsh vegetation. Coarse durable materials are more likely to be retained on the upper beachface and provide natural bluff protection within a relatively narrow width.

Extending seaward from the break in slope, the low-tide terrace typically consists of a gently sloping accumulation of poorly sorted, fine-grained sediment (Komar 1976, Keuler 1979). Considerable amounts of sand in a mixed sand and gravel beach are typically winnowed from the high-tide beach by waves (Chu 1985) and deposited on the low-tide terrace (Figure 1). Lag deposits derived from bluff recession are often found in the low-tide terrace. Lag deposits are the largest clasts (boulders) left behind, as bluffs and beaches receded and finer grain sediment was transported away. At some high-wave energy beaches, extensive lag deposits naturally armor the low-tide terrace. The width and slope of the low-tide terrace affects the degree of wave energy dissipation that occurs along a beach (Jackson and Nordstrom 1992).

Puget Sound and the Northern Straits have mixed sand and gravel beaches (Finlayson 2006), which differ from much more common sand beaches in that a significant proportion of gravel allows the slope of the beachface to be far steeper. Gravel-rich beaches can be as steep as 4:1 (horizontal:vertical), as compared to outer coast sand beaches that have slopes on the order of 100:1. This makes Puget Sound beaches “reflective” as compared to “dissipative”, in that the narrow beachface does not absorb wave energy as much as low slope beaches. Mixed beaches also function differently than purely gravel (shingle) beaches, which are very porous and less prone to erosion.

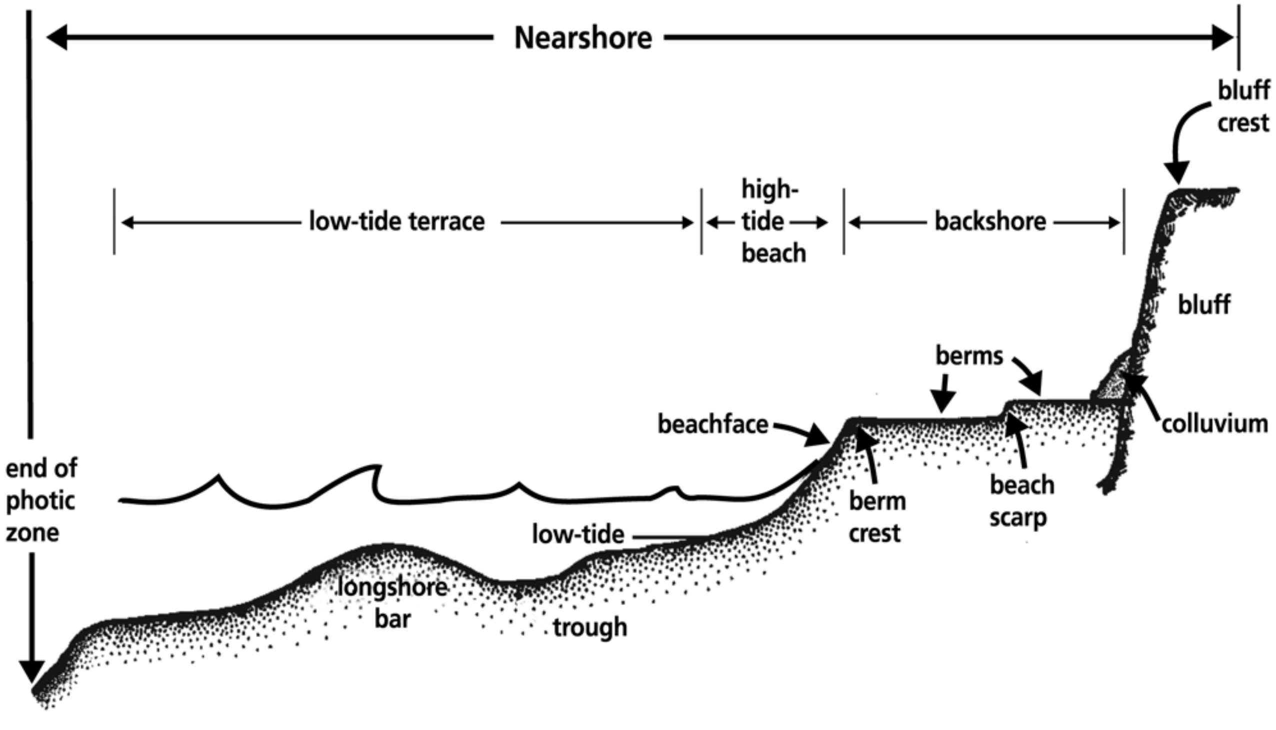


Figure 1. Cross-section of a beach with terminology used in the Puget Sound area (modified from Komar 1976). The entire area in the figure is now considered part of the nearshore zone in the Puget Sound region.

Beaches of the region typically have an active berm up to several feet higher than the elevation of mean higher high water (MHHW) and, except at more protected beaches, a higher elevation "storm berm" that is activated during high-water windstorms (Figure 1). Analysis of the Washington Department of Natural Resources (WDNR) Shorezone Database cross-shore attributes shows that approximately 27 percent of Puget Sound and Northern Strait shores have berms (WDNR 2001). Where there is room between the bluff toe and the berm(s), sandy backshore areas form, with drift logs, dunegrass and other salt-tolerant herbaceous vegetation present. WDNR (2001) reports that marsh vegetation is found in the supratidal area of approximately 18 percent of Puget Sound area shores, and driftwood in 27 percent.

Processes Affecting Beaches

Puget Sound beach morphology and composition are dependent upon exposure to wave energy and windstorms and available sediment sources. Outside of areas on the Strait of Juan de Fuca, Puget Sound area beaches are shaped by wind-generated waves. Wave energy is controlled by fetch: the open water distance over which winds blow without any interference from land. Puget Sound shores are fetch-limited due to isolation from ocean conditions, their highly convoluted shape and relatively low degree of exposure (Finlayson and Shipman 2003). Even with winds occasionally reaching more than 100 km/hour, short fetch distances strongly limit wave height. Winds from the south (southerly winds) are both prevailing (most commonly occurring) and predominant (strongest) (Finlayson 2006). Southerly windstorms and waves are most common in winter months. Summer brings lower velocity northerly winds. Beaches exposed to the south are therefore more subject to change, compared to beaches exposed to the north.

Within Puget Sound and the Northern Straits, calculated fetch exhibits considerable spatial variability. The WDNR Shorezone Database measured and classified the exposure of all beaches in Washington state based on a combination of several open water distance measurements (WDNR 2001). Semi-protected shores make up the largest number of beaches in the region (46 percent). Protected beaches account for 37 percent of the shores, while semi-exposed (10 percent) and very protected shores (7 percent) occur less frequently. Shores with the greatest exposure are located predominantly in the Northern Straits. Semi-protected shores are found throughout the north- and south-trending basins that dominate the central Puget Sound. Protected and very protected shores are typically located within the many fjord-like bays of the central-south sound. Very protected shores are found in the bay-head beaches, as well as within the major estuaries. Finlayson (2006) used a different method of calculating exposure that shows fetch data for Puget Sound as a continuum (Figure 2).

Puget Sound beach morphology is largely influenced by higher-energy conditions, such as those that occur during windstorms and act directly on the beach, backshore and bluffs (Figure 3). As a result, during periods of low wave energy, beach morphology can represent a storm artifact, or state of partial recovery, rather than equilibrium conditions (Nordstrom 1992, Finlayson 2006). Large waves that occur during high tides often result in overwash of beaches that lack bluffs behind them (barrier beaches). This results in the landward transport of sediment over the top of the berm(s) and the landward translation of the beach profile (Figure 4).

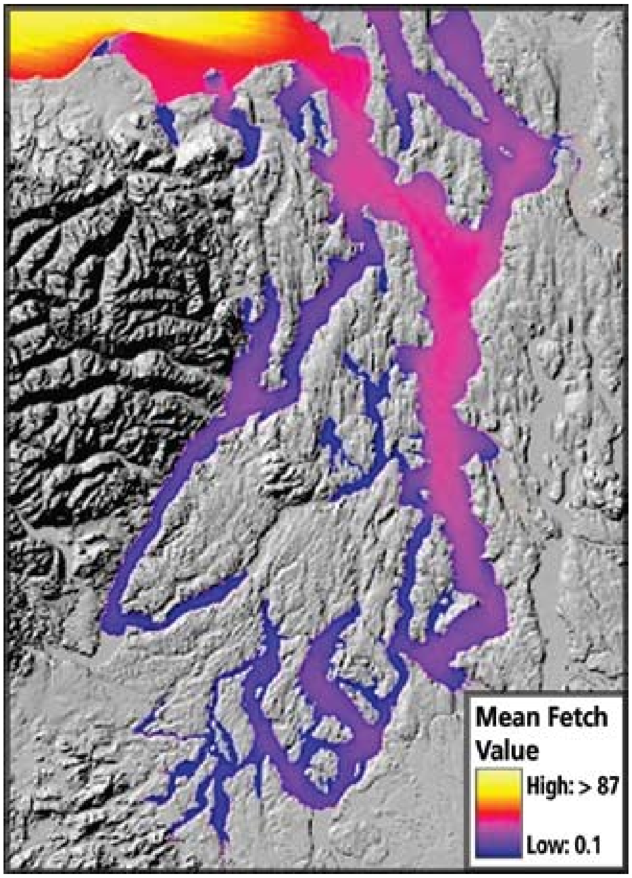


Figure 2. Mean fetch of Puget Sound shores (the mean of nine measured radials centered about the direction from which the wind blows; 90-meter resolution), from Finlayson (2006).

More readable color versions of this and all other graphics in this series are available at *www.pugetsoundnearshore.org/*.

As an example of the importance of occasional storms to the region's beaches, the significant southwesterly windstorm that occurred on Feb. 4, 2006, appears to have caused substantial upper beach, backshore and bluff erosion throughout the region (Figure 4). This storm coincided with very high water levels during the peak time of southerly and southwesterly wind and waves. Recorded tides at the National Oceanic and Atmospheric Administration (NOAA) water level stations showed peak water levels around two feet above the predicted very high tides, which brought water levels to near record highs (NOAA 2006). Winds reached 48 knots at Smith Island off northwest Whidbey Island at roughly the same time as peak water levels. The resultant erosion is still the subject of much concern around the region.

Figure 3. Example of high tide windstorm causing significant beach and backshore change at Rosario Resort in San Juan County.

Figure 4. Tombolo at southern Decatur Island, San Juan County, showing extensive overwash from the 2/4/06 storm, which deposited large volumes of gravel on the low energy side of the barrier (Johannessen).

Puget Sound beaches are composed primarily of sediment derived from bluff erosion (Keuler 1988). The composition of bluffs and local wave energy influence the composition of beaches. Waves sort coarse and fine sediment, and large waves can transport cobbles that small waves cannot. Additionally, beaches supplied by the erosion of coarse gravel bluffs will differ in composition from those fed by the erosion of sandy material. The exposed strata of the eroding bluffs in Puget Sound (discussed in *Puget Sound Bluffs* section, below) are largely composed of sand, gravel and silt (WDNR-DGER 2001). These same materials dominate sediment found on the beaches, with the exception of silt and clay, which are winnowed from the beachface and deposited in deeper water; these fine materials thus do not contribute to the active beach profile (Bray and Hooke 1997).

In most areas of the country, the greatest mobility of the beach is associated with sediment exchange between the upper and lower portions of the upper foreshore (Jackson and Nordstrom 1992). However, at mixed sand and gravel beaches with the common, distinctly different high tide beach and low tide terrace of this region, alongshore sediment transport (Kirk 1980) may be greater, although research on this in Puget Sound is acutely lacking. The region also appears to differ from many areas in the country in that there is often not a seasonal change in the beach profile, where winter storms create a lower elevation “winter beach” (with sediment moved to offshore bars), as compared to the higher “summer beach”. This cycle does occur locally at many beaches but is overshadowed by periodic, very large windstorms that cause less regular beach profile adjustment.

Net Shore-drift

To understand the processes controlling nearshore systems and their continued evolution, the three-dimensional sediment transport system in the littoral zone must be examined. The basic coastal processes that control beach dynamics will first be explained, and then put into the context of drift cells. Shore drift is the combined effect of **longshore drift** (the sediment transported along a coast in the nearshore waters) and **beach drift** (the wave-induced motion of sediment on the beachface in a longitudinal direction). While shore drift may vary in direction seasonally, **net shore-drift** is the long-term, net effect along a particular coastal sector (Jacobsen and Schwartz 1981). The concept of a drift cell has been employed in coastal studies to represent a sediment transport sector from source to deposition along a coast. An idealized drift cell is defined as consisting of three components: a site (usually an erosional bluff) that serves as the sediment source and origin of a drift cell; a zone of transport, where sediment may be deposited temporarily and waves transport sediment alongshore; and an area of deposition (and transport), which is the terminus of a drift cell (Jacobson and Schwartz 1981). In reality, sediment input occurs from different bluff reaches throughout a drift cell, and cell termini are not necessarily depositional.

The most important control on net shore-drift is waves, which provide the primary mechanism for sediment erosion, entrainment and transport. Wave fetch is the most important factor controlling net shore-drift in more protected (fetch-limited) environments (Nordstrom 1992). The orientation of a shore reach dictates the maximum fetch that acts on the reach, which is the direction of the greatest potential shore-drift.

Dr. Maurice Schwartz and students at Western Washington University mapped net shore-drift cells throughout Puget Sound and the Northern Straits from the late 1970s to the early 1990s. The Washington Department of Ecology (DOE)

Shorelands Division published a compilation of these mapping products (Schwartz et al. 1991, Johannessen 1992), which are now referenced as Schwartz et al. (1991). Net shore-drift studies were conducted through systematic field investigations of the coast to identify geomorphologic and sedimentologic indicators that revealed net shore-drift cells and drift direction (Jacobsen and Schwartz 1981). The mapping methods applied well-documented, isolated indicators of net shore-drift in a systematic fashion (for example, Figure 5). The mapping presentation, however, was rudimentary by current standards.

The earliest local drift cell mapping was performed by Bauer (1976). A different drift cell mapping effort was published in the Coastal Zone Atlas of Washington series (WDOE 1978-80). The methods used in that study differed greatly from those applied by Schwartz et al. (1991) in that the Atlas relied exclusively on very limited historic wind records (wave hind-casting). Drift directions indicated in the Atlas have repeatedly been proven inaccurate (Johannessen 1992) and should not be used. Recently, the WDOE digitized the compiled mapping of Schwartz's students (Figure 6); however, the mapping was not technically reviewed, and numerous errors are being corrected in the digital dataset at present.

Puget Sound contains 860 net shore-drift cells and approximately 233 regions of no appreciable net shore-drift. Drift cells range in length from 46 feet to just under 19 miles, with the average drift cell just under 1.5 miles long (Schwartz et al. 2001). The wide range of drift cell lengths can largely be attributed to frequent changes in shoreline orientation, thus the compartmentalizing of longshore drift into numerous shorter cells (Schwartz et al. 1991). The general pattern of littoral transport in the region largely reflects the shore orientation relative to the predominant (strongest) wind and wave conditions. Shores exposed to the south typically have northward net shore-drift, due to predominant southerly winds. Shores exposed only to the north are within the wind and wave shadow of strong southerly wind conditions but are exposed to lighter northerly winds, resulting in southward transport. Shores oriented east and west are similarly influenced by their shore orientation, relative to direction from which the greatest fetch is derived. No appreciable net shore-drift occurs along rocky shores or in enclosed shorelines such as the inner shores of lagoons and small estuaries.

Few net shore-drift rate calculations have been made in the Puget Sound region, and most are in a paper by Wallace (1988). Drift cell analyses that look at coastal processes in detail in a particular drift cell(s) have been completed for fewer areas (for example Shipman 1998, Johannessen and Chase 2003). This also represents a data gap. Additional quantitative studies, including historic shore change work and the development of quantitative sediment budgets, would greatly help our understanding of net shore-drift processes.

Figure 5. Example of net shore-drift cells from southeast Whidbey Island (Johannessen 1992). Presentation is from Washington Department of Ecology's Digital Coastal Atlas.

More readable color versions of this and all other graphics in this series are available at *www.pugetsoundnearshore.org/*.

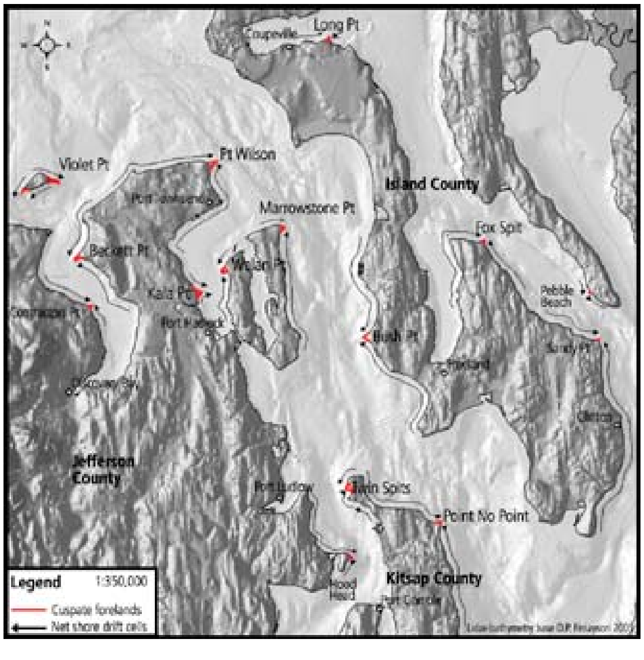


Figure 6. Occurrence of cuspate forelands with associated drift cells in north-central Puget Sound (based on Keuler 1988, Johannessen 1992 and Schwartz et al. 1991).

Beach Landforms

A wide variety of coastal landforms have evolved through net shore-drift in the Puget Lowland. Coastal evolution tends to straighten coasts over time. The Puget Lowland has relatively immature, crenulated coasts that have been straightened far less than more mature coasts, such as in the southeastern United States. The Puget Sound area can be considered in an interim stage where erosion of headlands and the formation of large spits have partially straightened the coast. Other than bluff-backed beaches, spits are the largest general group of depositional landforms created through sediment transport from easily eroded headlands. Spits often extend from the coast where the shore orientation changes. Spits can be near linear, recurved, or form as a complex of multiple spits (Zenkovich 1967). Many examples of near linear or recurved spits are present throughout the sound and Northern Straits. Many were developed with houses, which pose serious coastal flooding and erosion hazards, as these landforms are dynamic and periodically experience overwash (with erosion of the waterward beachface) and flooding. Dungeness Spit, in Clallam County, is an example of a complex spit, with net shore-drift causing sediment transport to rotate around the spit making an almost 270° clockwise turn.

Another type of spit found locally is the cuspate foreland, sometimes referred to as a cuspate spit. These are triangular depositional features, with straight or concave shores extending out to a seaward point (Uda 2005). Cuspate forelands are fairly common and widely distributed across the region (Figure 6). They are typically formed by the convergence of two drift cells from opposite directions, often at the narrowest part of an inlet or large bay. Examples are Beckett Point, in Discovery Bay, and Point No Point and West Point in the Main Basin, which have prograded into deeper water. These landforms may be migrating in one direction, with erosion typically occurring on the south side and deposition on the north. Cuspate forelands often have coastal wetlands in the center, where two spits have converged, but in many locations, the wetlands have been filled.

Tombolos are a less common depositional landform of the region. These are barriers that extend above high water and link a former island to the mainland or link two islands. Tombolos are found in areas with numerous islands, such as at Hood Head near the Hood Canal Bridge (Figure 6), and at both ends of Decatur Island in the San Juan Islands (Figure 4). Another group of large depositional landforms is bars, which are subtidal or extend into the intertidal, such that they are covered at high water. One common form of bar found on local low-tide terraces is the transverse bar (Finlayson 2006), which often can be used to infer the short-term littoral drift direction.

Coastal landforms are often found in predictable locations within net shore-drift cells. An idealized drift cell has feeder bluffs (areas of sediment input to the beach system) at the cell origin and often along the bluffs of the cell (Figure 7). Landslides and bluff slope both commonly decrease along a drift cell (with many exceptions). When bluff sediment input becomes negligible, the bluff is classified as a transport zone. Accretion shoreforms begin where broad backshore areas and spits are present, which can be the location of important habitats such as forage fish spawning beaches and spits fronting salt marshes (Figure 7). Wolf Bauer (1976) first coined the term accretion shoreform, which has been applied to all depositional coastal landforms in the region (including spits) that extend above MHHW. This term has been used while mapping geomorphic shore types in recent years, sometimes with additional classification as to the depositional process (Johannessen et al. 2005).

In a recent study of the shores of Water Resource Inventory Areas (WRIA) 8 and 9 (King and southern Snohomish Counties, Washington), it was estimated that accretion shoreforms occurred along 33 percent of the shore during pre-development conditions (Johannessen et al. 2005). These landforms were primarily created by deposition at longshore lagoons, stream mouths and depositional open beaches. In almost all cases, deposition occurred as a result of a change in shore orientation (Johannessen et al. 2005). Spits encompassed the longshore lagoons, while depositional open beaches did not have lagoons or other water bodies associated with them. Recent mapping in all of Island County found that accretion shoreforms occurred along 37 percent of the shore (Johannessen and Chase 2005). Examples of Whidbey Island accretion shoreforms are the large spits in Cultus Bay at the termini of both drift cells and the broad beach and backshore around the community of Possession within the long drift cell (Figure 8).

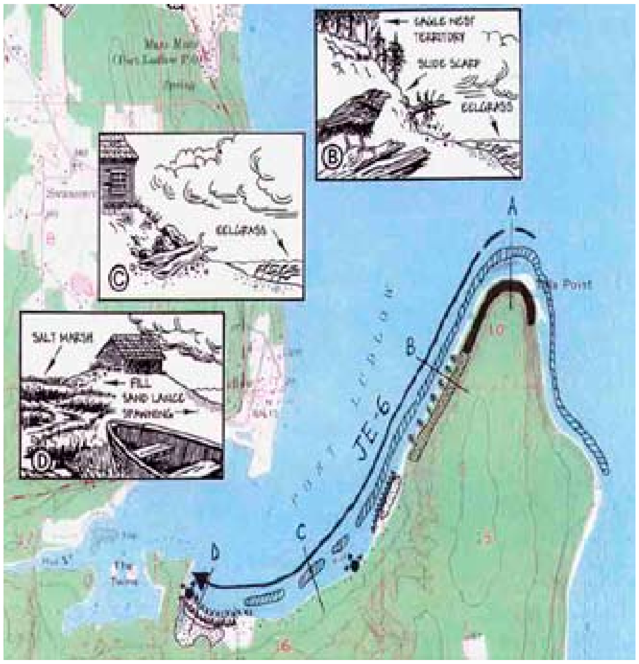


Figure 7. Net shore-drift cell JE-6 in eastern Port Ludlow Bay and associated landforms and habitats (Johannessen 1999).

More readable color versions of this and all other graphics in this series are available at *www.pugetsoundnearshore.org/*.

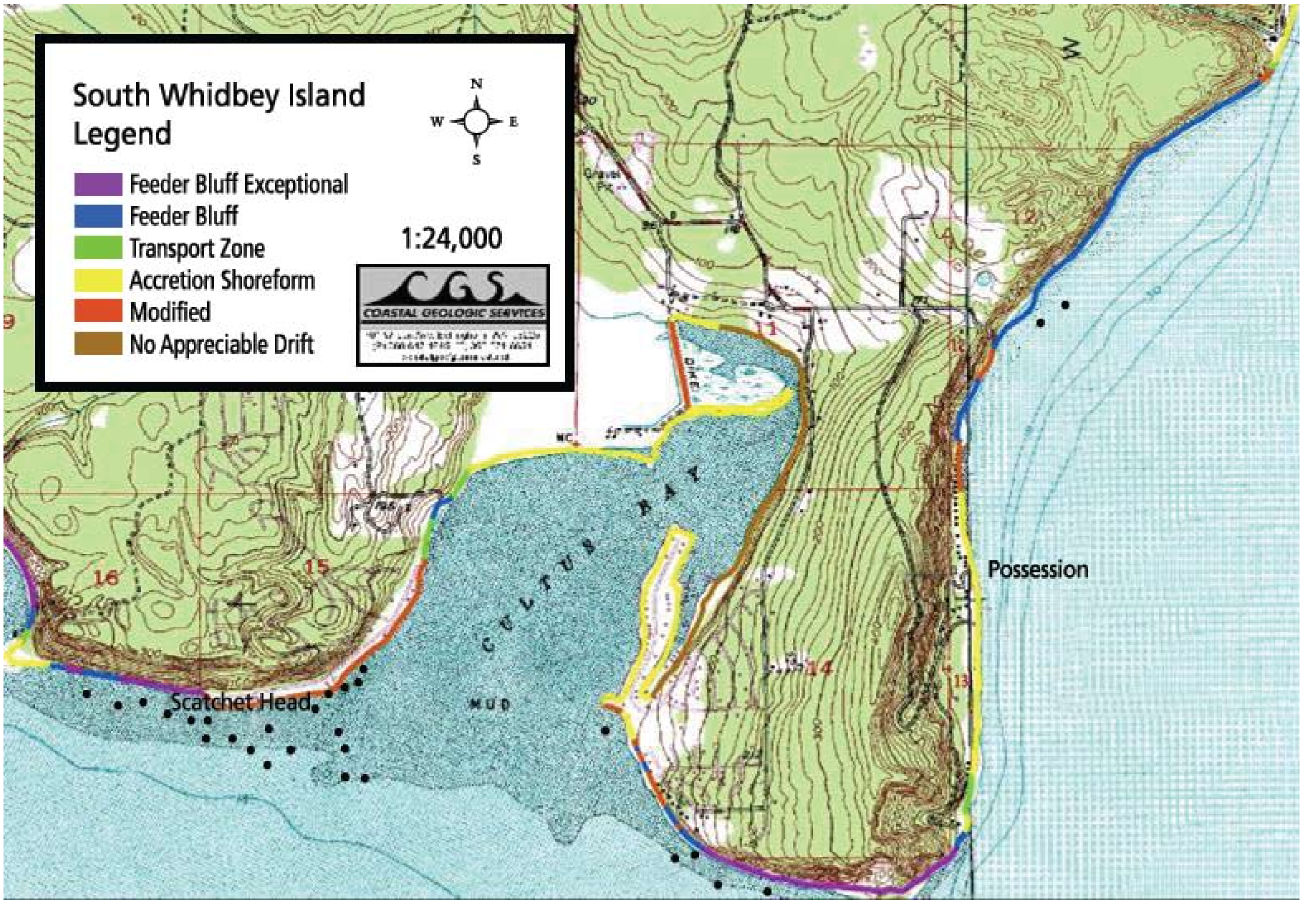


Figure 8. Classification of feeder bluffs and accretion shoreforms at southeast Whidbey Island (Johannessen and Chase 2005).

More readable color versions of this and all other graphics in this series are available at *www.pugetsoundnearshore.org/*.

Puget Sound Bluffs

Bluffs are ubiquitous landforms, occurring along approximately 80 percent of the earth's coasts and more than 60 percent of Puget Sound shores (Emery and Kuhn 1982, WDNR 2001). Bird (2005) defines bluffs as "bold, steep sometimes rounded coastal slopes on which soil and vegetation conceal, or largely conceal the underlying rock formations, in contrast with a cliff in which these formations are exposed". Coastal slopes cut into unconsolidated sediment in the Puget Sound area are typically referred to as bluffs.

Puget Sound was created by the repeated advance and retreat of glacial ice sheets, the most recent of which advanced between 15,000 and 13,000 years ago (Booth 1994). Glacially derived sediment dominates the Puget Lowland (Booth 1991, Easterbrook 1992) and, along with less common interglacial sediment, is exposed in coastal bluffs. During the maximum extent of the ice sheets, sub-glacial meltwater and scour by the ice sheets carved the deep, linear troughs that are now occupied by the region's marine waters and large lakes. As the glacial ice sheets melted and sea level rose, the earth's crust beneath the ice slab uplifted. This stage of uplift was completed and the crust stabilized at (near) its preglacial level, approximately 5,000 years ago (Downing 1983). This is thought to be the time when the bluffs and major spits of Puget Sound began to evolve to their current form.

The bluffs found in Puget Sound and Northern Straits are far from homogeneous in character and display high spatial variability due to differences in upland relief, geologic composition and stratigraphy, hydrology, orientation and exposure, erosion rates, mass wasting mechanisms, and vegetation (Shipman 2004). Most Puget Sound bluffs consist of a sequence of glacial and interglacial sedimentary units. Generally, the unconsolidated bluffs of the Northern Straits have more variable geology than the central and southern sound. Northern Straits bluff geology is unique due to the north experiencing greater isostatic rebound, its sea level history, and an abundance of bedrock terrain (Shipman 2004). Bedrock shores are found in the San Juan Islands area, on the Olympic Peninsula, and in the central sound between Seattle and Bremerton.

Figure 9. Common bluff configurations in Puget Lowland (from Shipman 2004). A, high bluffs composed of poorly consolidated outwash gravels. B, 300-ft high bluff in Tacoma consisting primarily of advance glacial outwash. C, ~45-ft bluff in southern Puget Sound composed of compact sediments that form near vertical slope, also note colluvium at toe of bluff. D, Northern Puget Sound bluffs, exhibiting steeper bluff toe profile, with toe erosion.

The strata of glacial material that comprises the majority of Puget Sound bluffs represents the variety of processes responsible for their deposition (Downing 1983). One of the most common glacial deposits found in Puget Sound bluffs is glacial till, which is highly consolidated, poorly sorted sediment deposited directly under glacial ice sheets. Outwash sands and gravels deposited by streams that drained the advancing ice sheet, and laminated clay beds formed on lake bottoms at the edge of the glacier, are also common bluff strata (Easterbrook 1982). Outwash sands were deposited prior to Vashon Till and are therefore found vertically below till (Booth 1994). Glaciomarine drift that was deposited near the end of the last glaciation is also widespread in the north sound, and is present in the upper bluffs above older deposits (Lapen 2000). Figure 9 shows examples of different Puget Sound bluff strata and configurations.

The Vashon Formation was deposited during the most recent ice sheet advance and is the most common glacial stratigraphic sequence observed in the upper portions of Puget Sound bluffs. It comprises older lakebed silts and clays deposited in pro-glacial lakes (Lawton clay) in lower elevations. This is usually overlain by a thick unit of advance outwash sands and gravels (often called Esperance sand) and capped with Vashon till (Gerstel et al. 1997). Glacial till is typically highly resistant to erosion and often forms steeper slopes than other geologic units of the Puget Lowland. Table 1 displays the strata that make up the majority of Puget Sound bluffs, their relative resistance to erosion and typical bluff gradients.

Bluff Processes Overview

Bluff processes are the cumulative result of numerous interacting variables, including the first-order factors of climate and sea level rise, and second-order, site-specific factors (Figure 10; Bray and Hooke 1997). Site-specific factors include the characteristics of the bluff (cliff) material — its composition, resistance, permeability, slope structure, bluff weaknesses — and local topography, including the slope's landslide history (Emery and Kuhn 1982). Other site-specific factors include hydrodynamics, the protection offered by the beach, and management practices (discussed below). These factors produce spatial and temporal variability in the processes and forms that characterize eroding bluffs (Bray and Hooke 1997). Second-order, or site-specific, drivers of erosion are commonly grouped as marine, subaerial, or human-induced erosion. Each driver may be occurring independently or simultaneously upon the bluff across time. In Puget Sound, bluff erosion is typically driven by a combination of all of these factors, as seasonal drivers such as storms interact with locally variable bluff geology, toe (basal) protection and other factors, including management practices.

Coastal bluffs are the primary source of sediment for most Puget Sound beaches (Keuler 1988, Downing 1983). Mass wasting (landslides) and erosion of these bluffs deliver sediment to the beach in large quantities. A secondary sediment source is rivers and streams, but these are thought to contribute only on the order of 10 percent of beach sediment (Keuler 1988).

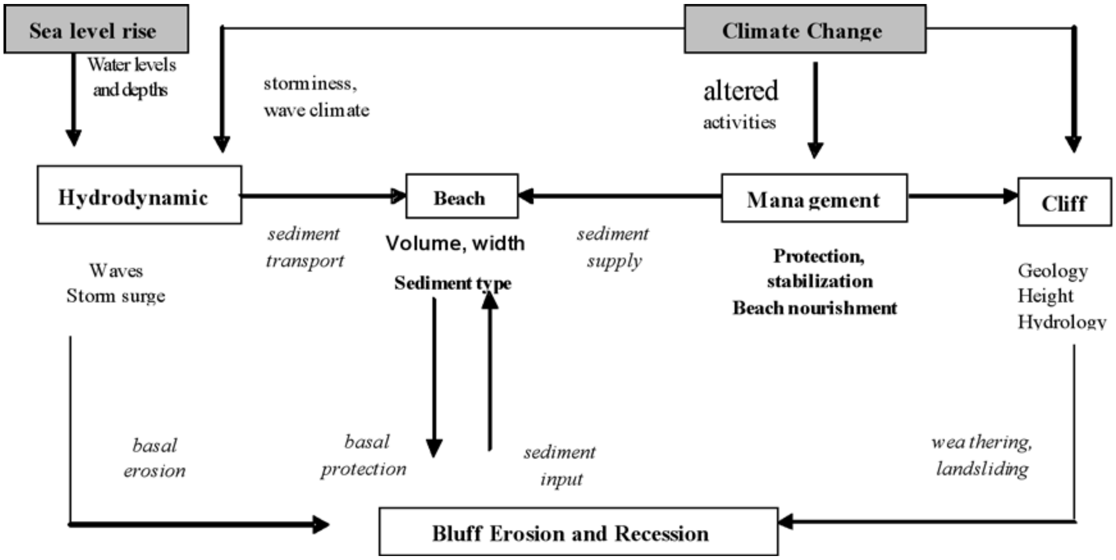


Figure 10. Summary of factors influencing bluff erosion (Bray and Hooke 1997).

Marine Erosion

Marine-induced bluff erosion is the dominant type of erosion; in combination with bluff geology, it shapes the bluff profile (Figure 11). Marine erosion exhibits a general cycle that occurs along all coastal bluffs. The cycle is initiated when sediment grains, blocks or slabs detach from the bluff face and slide down the slope. The material deposited at the base or toe of the slope is referred to as colluvium. This colluvium buffers the base of the bluff from wave attack and in the process is slowly removed by wave action. Once the waves have eroded the colluvium, they erode the base of the bluff causing bluff undercutting, also referred to as toe erosion, which destabilizes the slope, and the cycle repeats itself (Emery and Kuhn 1982), generally at the time scale of several decades in the Puget Sound region.

In Puget Sound, bluff toe erosion rates are relatively slow and essentially set the stage for future slope failures (Shipman 2004). However, toe erosion is rarely the sole trigger of a landslide, as there is usually a lag time between loss of support at the toe and failure of the upper slope (Emery and Kuhn 1982). Climatic conditions combined with bluff stratigraphy are of greater influence in initiating slides (Gerstel et al. 1997, Johannessen and Chase 2003). Marine-induced erosion exhibits some seasonality due to heightened storm activity during winter months. Storms that coincide with elevated water levels, such as a storm surge or an extraordinary higher-high tide, often initiate landslides throughout the Puget Sound region (Johannessen and Chase 2003). The wave attack caused by a storm that occurs in conjunction with heightened water level can produce dramatic toe erosion, which then undermines and destabilizes a larger portion of the bluff that may not fail (slide) until subsequent wet-weather months.

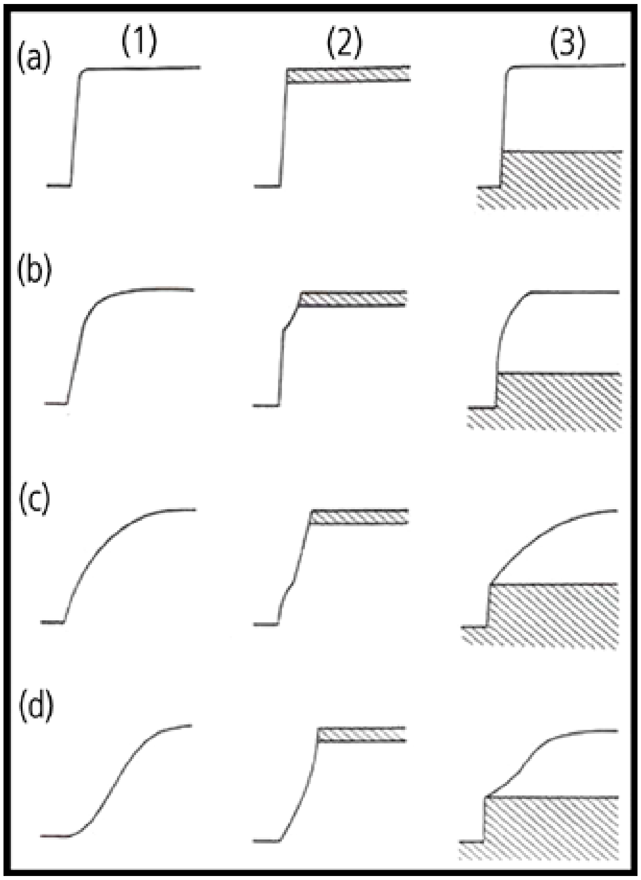


Figure 11. The effects of marine and subaerial processes and variable rock hardness on bluff profiles. Columns 1, 2, and 3 represent homogeneous rocks, harder rocks (shaded) at the top of the bluff, and harder rocks at the base of the bluff, respectively. Rows a, b, c and d represent environments in which marine erosion is much greater than, greater than, equal to and less than subaerial processes (Emery and Kuhn 1982).

Bedrock shores, such as those found in the San Juan Islands, are also subject to mass wasting, though it typically occurs at dramatically slower rates than the unconsolidated glacial and peri-glacial deposits found in the central and south sound. In Skagit County, Keuler (1979) identified a consistent difference in the erosion rates between massive rocks and those with dense jointing or were otherwise more erodible. These sea cliffs are typically excavated by wave scour and weathering processes. Rocks are attacked by quarrying; the hydraulic pressure of breaking waves forces air and water into fissures, which slowly dissects the rock along planes of weakness (including joints and faults) to form clefts and gullies (Bird 2000).

Subaerial Erosion

Subaerial erosion includes gullying, rainwash and slumping/mass movements (induced by groundwater or frost wedging). Subaerial erosion tends to make the bluff top broadly convex upwards, with short-term concavities associated with local runoff, mass movement or notching by groundwater (Figure 11; Emery and Kuhn 1982). Most landslides in Puget Sound occur as a result of subaerial erosion in response to either heavy precipitation, initiating shallow failures, or elevated groundwater conditions, which have been known to reactivate large, deep-seated landslides (Thorson 1987, Shipman 2004).

Precipitation frequently leads to destabilization of Puget Sound bluffs due to contrasting slope-forming processes (lithologic, hydrologic and mechanical properties) of the underlying strata (Tubbs 1974). This can lead to complex bluff profiles containing both steep and gradual segments (Shipman 2004). For example, when permeable outwash sands (Esperance sands) overlie impermeable glacial lake clays (Lawton clay), a contact point is formed, with saturation of the lower sands common, leading to upslope failures. In the winter-spring of 1972, a time of anomalously high landslide occurrence in Seattle (50 reported landslides), 40 percent of all slides occurred along this contact zone (Tubbs 1974). As a result, many Puget Sound bluffs have mid-slope benches that occur at this contact zone (Figure 12, Gerstel et al. 1997). Similarly, when permeable glacial units overlie

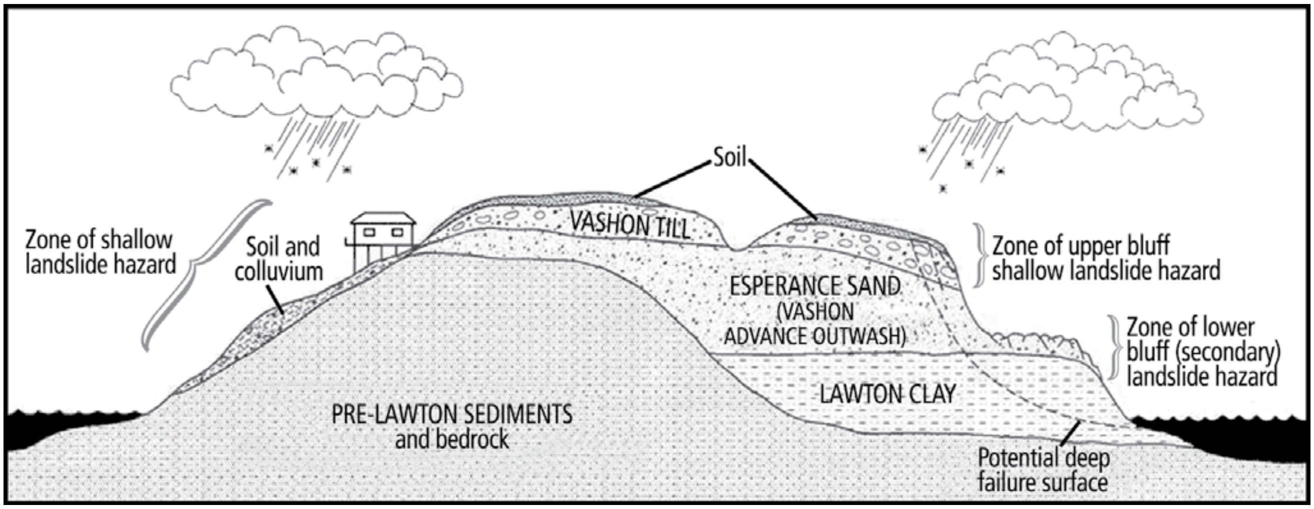


Figure 12. Cross-section of the characteristic stratigraphy responsible for landsliding in the central Puget Sound. The units displayed are not necessarily laterally continuous over long distances, and they can be more complex, with several water-perching layers. The Esperance Sand and Lawton Clay are unit names restricted to the central sound; however, similar sequences are present elsewhere in the Puget Lowland (Gerstel et al. 1997).

bedrock, water collects and lifts the overlying (permeable) material, resulting in upslope failures (Bird 2000, Gerstel et al. 1997).

The contrasting slope-forming properties of different stratigraphic units also influence the bluff gradient. Geologic units that are more resistant to (basal) erosion are often of higher gradient. However, steeper slopes are also more prone to landslides due to gravitational stresses. Variations in rock strength and hydrologic conditions complicate this correlate (Shipman 2004). General observations of the relative resistance to erosion and the typical bluff gradient of common geologic units of Puget Sound bluffs are found in Table 1.

Table 1. Common geologic units of Puget Sound bluffs (based on Shipman 2004 and Easterbrook 1976).

Geologic unit	Resistance to erosion	Typical bluff slope
Glacial Till	High	High
Glaciomarine drift	Moderate	High
Advance outwash (Vashon)	Variable-low	Variable-low
Pre-Vashon fluvial sediments	Variable	Variable
Recessional sands and gravels	Low	Angle of repose

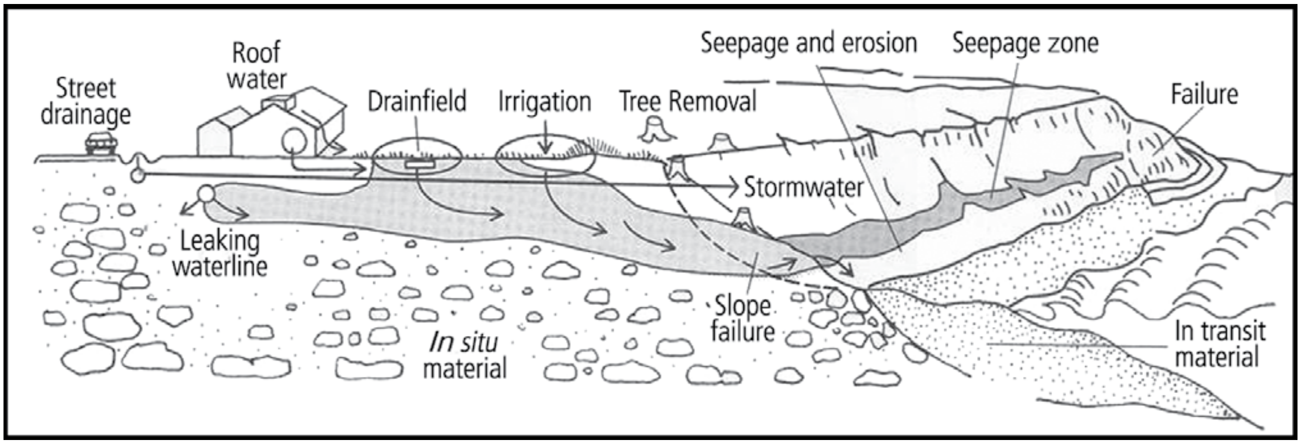


Figure 13. Common sources of bank stability problems related to land use alterations of drainage and vegetation (Marsh 2005).

Human-induced Erosion

The third driver of bluff erosion is human-induced erosion, which comes in many forms. Bluff erosion can be exacerbated and initiated by overloading the top of a bluff, cutting into the toe of the slope, grading and removing stabilizing soil, removing dunes and vegetation and, most importantly, adding water (Emery and Kuhn 1982, Shipman 2004). Common problematic water additions include increased surface water runoff resulting from impervious surfaces, vegetation removal, and poorly designed drainage, lawn watering, and septic tank leach lines.

Surface water volumes often increase and become more concentrated as a result of housing and road development, causing decreased infiltration and interception of water (Montgomery et al. 2000). Concentrated surface water can locally erode bluff crests and saturate soils, which exacerbates slope stability problems and can trigger landslides (Shipman 2004). Runoff flowing down a driveway and rapidly across a lawn (which can absorb little water when wet) as sheet flow to the bluff face is an example of this process. Failed tightlines on a bluff face (constructed out of low-strength corrugated pipe) have often contributed to initiating coastal landslides. Overall, more than 70 percent of slope failures that occurred during the heavy rainfall events in Seattle in 1997 were at least partially due to human actions (Shannon and Wilson 2000).

Removal of bluff vegetation can result in low root strength (of scattered ornamental plants and grass) and increased likelihood of future landslides (Schmidt et al. 2001, Bishop and Stevens 1964). Bluffs with significant modifications to both the natural drainage regime and vegetation are particularly susceptible to landsliding. Reestablishment and maintenance of native vegetation cover, or installation of a fibrous-rooted vegetation cover, along with some type of drainage control, can reduce the likelihood of bank failures (Gray and Sotir 1996, Menashe 1993, Roering et al. 2003).

Figure 13 depicts the common actions that result in human-induced erosion.

Erosion Rates

Long-term bluff recession rates in Puget Lowland are dependent upon the level of wave action the beach receives (marine erosion), the geology of the bluff, and the characteristics of the adjacent beach (Shipman 1995, Keuler 1988). Broad beaches, high storm berms and cobble-boulder lag deposits in the lower beach can buffer the bluff toe from wave attack. However, where beaches are starved of sediment due to either natural or artificial circumstances, the erosion rates of associated bluffs may accelerate (MacDonald et al. 1994).

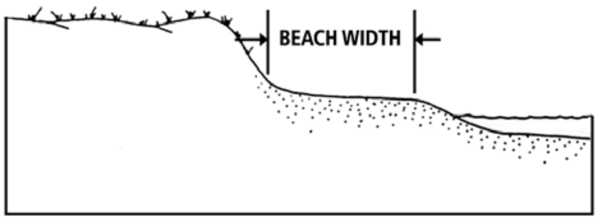
Little quantitative research has focused on bluff recession rates in Puget Sound. Shipman (2004) and Keuler (1988) report that erosion rates have high spatial variability, which apparently reflects small variations in shoreline orientation and beach characteristics, combined with lateral variability in geology found at the bluff toe and along the shore platform. Based on the limited research that has been performed throughout the region, it is generally accepted that the highest erosion rates are found in the Northern Straits due to (relatively) greater wave exposure and poorly consolidated sediments. Typical erosion rates in the Northern Straits are on the order of 2-10 cm/yr (Keuler 1988). Common erosion rates farther south are apparently on the order of a few centimeters a year, or less, in most areas (Shipman 2004). More research into the local mechanisms and rates of marine bluff erosion would be very useful.

Shore Modifications

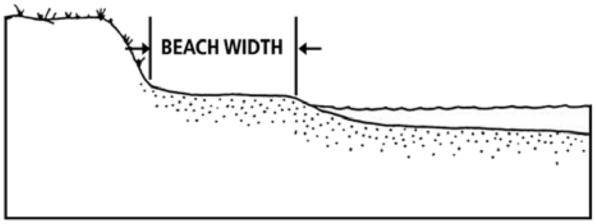
A substantial portion of Puget Sound and Northern Straits shores has been modified from its original state. Shoreline modifications occurring within the study area include shoreline armoring (bulkheads consisting of rock, concrete and timber), large revetments (sloped face to protect a bank or shore structure, usually constructed of rock), causeways (fill corridors that extend across embayments), groins (cross-shore structures designed to trap sediment), overwater structures, fill, and dredging. Approximately 34 percent, or 805 miles, of the study-area shore have undergone such modifications (WDNR 2001), though additional modifications likely exist due to the challenge of documenting more subtle alterations, such as dredging and filling.

Shoreline Armoring

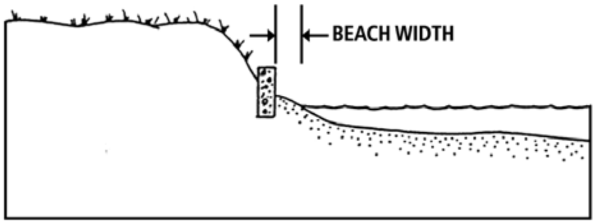
Shoreline armoring is a general term used to describe erosion control structures, such as bulkheads (often called seawalls) and rock revetments that are used to protect coastal property. These structures are usually shore-parallel and are intended to stop coastal erosion or protect fill from marine erosion. Historically, armoring the shore was the most common approach to reduce the impacts of marine induced erosion and to slow or halt coastal retreat. Bulkhead construction has slowed, but even with the advent of local shoreline management restrictions, it has continued, due to improper house siting prior to the use of setbacks and the redevelopment of small lots. In addition, as property values have risen, less appealing, highly erosive lands are being developed. Preventing shoreline retreat and attempting to curb erosion are active attempts to preclude natural processes from occurring, as shorelines are not stagnant features and are guaranteed to migrate over time. As a result, coastal erosion and shoreline retreat are typically only viewed as problematic when structures are built in areas that are exposed to erosion or wave attack (Griggs 2005). Passive erosion refers to the shore erosion that was occurring prior to any modifications. Figure 14 shows how passive erosion can result in the loss of the upper beach area after a bulkhead is installed.



(A) Initial shoreline profile showing beach width.



(B) Shoreline profile after sea level rise and associated dune or bluff erosion. Although shoreline has migrated landward, beach width remains the same.



(C) Shoreine profile following sea level rise where seawall has fixed shoreline position. Note reduced beach width.

Figure 14. Example of beach width loss through passive erosion (Griggs et al.1994).

Shore-normal structures called groins and jetties are another group of coastal structures. Groins are constructed perpendicular to shore in an attempt to prevent erosion by slowing sediment transport alongshore. The structure is typically designed to accumulate sand on the up-drift side, but there is a corresponding loss of beach material on the down-drift side (Davis 2005). This phenomenon commonly results in the construction of multiple groins along a beach, in what is referred to as a groin field. Groins commonly are low profile and constructed of cement, wood or rock. Groins are also used for retaining sediment along beach nourishment sites or protecting adjacent natural areas from excessive sedimentation (Nordstrom 1992). Jetties are also shore-normal structures; however, they are typically larger and are used to protect harbors, marinas, tide channels and piers, and often indirectly act as large dams to sediment transport. Like groins, jetties typically capture sediment on the up-drift side of the structure and reduce sediment supply along the down-drift beach. A common cost-effective and efficient method of mitigating this impact is through sediment bypassing (moving sediment to the down-drift beach). An additional problem arises when waves refract (bend) around a groin or jetty, causing the wave energy to become focused on a specific section of shore; this exacerbates erosion and structure damage on the down-drift side of the structure (Davis 2005).

The impacts of armoring to beaches, primarily due to shore-parallel structures, are considerable and include aesthetic impacts, reductions in beach access, loss of beach due to structure placement, impacts to sediment supply, accelerated or induced erosion rates from shoreline defense structures, and beach loss as sea level rises and the beach is reduced in size (Griggs 2005). Numerous indirect and direct impacts to the ecology of the nearshore have also been identified, and will be described further in the next section.

Historic Versus Current Bluff Conditions

A recent study of current and historic coastal geomorphic conditions in the central Puget Sound (Water Resource Areas 8 and 9; Johannessen et al. 2005) focused on documenting current and historic bluff sediment sources. Results show that only 36.6 percent of the historic bluff sediment sources are still intact across the study area. Prior to development and the advent of shoreline modifications, sediment sources accounted for approximately 50.3 percent of the shore length, contrasted to current conditions of only 18.4 percent (Johannessen et al. 2005). Additionally, 22 drift cells (out of 61 cells in the study area) no longer had any remaining bluff sediment sources intact. Although the cumulative impacts to the coastal geomorphic system and nearshore habitats resulting from severe anthropogenic loss of sediment supply are unknown, impacts are likely to be substantial and pervasive. The impact to the nearshore systems resulting from this degree of alteration may take years to decades to become fully evident, as geomorphic processes often involve time lags (Brunsden 2001).

Of all the negative impacts of shore armoring in the Puget Sound area, sediment impoundment is probably the most significant (MacDonald et al. 1994). A structure such as a bulkhead, if functioning correctly, "locks up" bluff material that would otherwise be supplied to the shore drift system. This results in a decrease in the amount of drift sediment available for maintenance of down-drift beaches. The negative impact of sediment impoundment is most pronounced when armoring occurs along actively eroding bluffs, known as feeder bluffs (MacDonald et al. 1994; see sidebar: *Historic Versus Current Bluff Conditions*).

The effects of bulkheads and other forms of shore-parallel armoring on physical processes have been the subject of much concern in the Puget Sound region (for example, PSAT 2003). MacDonald et al. (1994) completed an extensive series of studies documenting the impacts to the beach and nearshore system caused by shore armoring in Puget Sound. A recent study in Thurston County using pairs of beach profiles at unbulkheaded and bulkheaded shores inferred that beach width, shade and drift log abundance were all significantly lower at bulkheaded sites (Herrera Environmental Consultants 2005). Additional studies on impacts from shoreline armoring have quantitatively measured conditions in front of a bulkhead and at an adjacent unbulkheaded shore. Data from other regions have shown that, in front of a bulkhead, the suspended sediment volume and littoral drift rate increase substantially compared to adjacent unarmored shores, which results in beach scouring and lowering along armored shores (Miles et al. 2001). These impacts are known as "active erosion," in that they appear to be caused by the bulkheads.

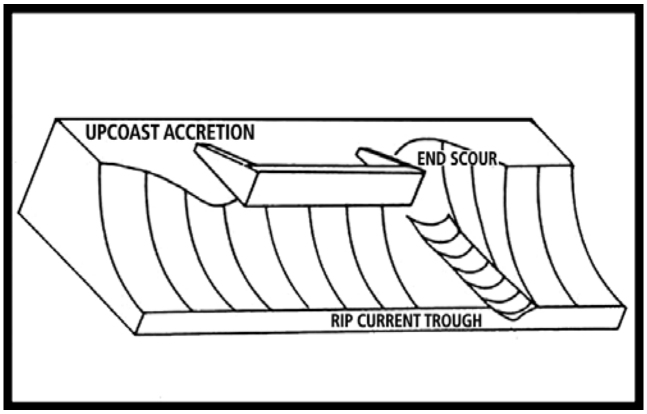


Figure 15. Types of beach response observed by Griggs and Tait (1990) after berm retreats landward of bulkhead.

A number of poorly documented local hydraulic impacts occur in response to a bulkhead. These include the formation of a scour trough (a linear depression) directly in front of the wall, probably as a result of increased reflectivity of the wave energy from the wall to the upper beach. Another hydraulic response is the formation of end scour erosion ("end effects" or end "scour") (Figure 15). This occurs at unprotected shores adjacent to the end of a bulkhead (Tait and Griggs 1991), where the wave energy is refracted, causing beach and bluff toe erosion. A rip current trough may form near the down-drift end of a bulkhead that interacts with waves. During-storm impacts, where seabed fluidization and scour occur at enhanced levels, may be pronounced in front of a bulkhead, but this process is not well understood.

The groundwater regime is often modified by the construction of a bulkhead that extends vertically above ordinary high water mark (OHWM) along the base of a bluff (MacDonald et al. 1994). This can cause increased pore pressure in beach sediment, leading to mobilization of beach sediment under lower energy waves relative to unbulkheaded conditions. This effect is most pronounced at locations with fine-grained beach sediment. Additionally, the extent of cumulative impacts from several long runs of bulkheads is a subject of great debate in the coastal research and management communities.

As bluffs in the study area continue to gradually recede, there will likely be a continued desire for homeowners to build bulkheads. This would lead to further sediment impoundment and further reductions in the natural sediment supplied to the nearshore system, and would therefore constitute a significant negative impact. A further decrease in the volume of net shore-drift sediment will eliminate maintenance of down-drift habitats.

Overwater Structures

Overwater structures are found throughout Puget Sound and Northern Straits, but are most abundant within urban and industrial areas. Overwater structures impact ambient wave energy, which can alter the size, distribution, and abundance of beach substrate (Nightingale and Simenstad 2001). The close placement of pilings diminishes wave energy and littoral transport rates, thereby causing finer sediments to fall out of suspension where they would normally remain in transport. This results in shoaling beneath and around pilings that support overwater structures such as piers and wharfs.

Mining-Quarrying

Most of the economically recoverable coastal zone resources worldwide are sand and gravel deposits (Osterkamp and Morton 2005). The principal uses of beach sand and gravel include aggregate in cement and asphalt for construction, road base, earth fill, and a variety of industrial products (Osterkamp and Morton 2005), along with gravel for drainage trenches. Mining of coastal zone sand and gravel in the Puget Sound area has occurred for many decades; however, based on anecdotal and limited information (Johannessen 2002), it appears beach mining linked to a heightened demand for aggregate was greatest in the middle of the 20th century. Beach mining is known to have been fairly common in the sound and the Northern Straits. For example, in Birch Bay and the San Juan Islands, older residents concur that large quantities of aggregate were extracted from beaches for early road construction; however, published information on this is generally absent. Gathering data through interviews (oral histories) before elders are gone would help fill this data gap and our understanding of the relevance of different types of beach sediment loss.

Additionally, large volumes of aggregates were extracted from open-pit quarry mines on Puget Sound bluffs (Johannessen et al. 2005) that would have supplied down-drift beaches with sediment. The impacts to associated drift cells resulting from the loss of sediment have not been formally addressed; however, altered conditions have been documented in association with the mines (Johannessen et al. 2005).

Filling and Dredging of Nearshore Areas

Considerable fill has been placed in the Puget Sound nearshore. The exact amount of intertidal and supratidal areas lost to fill has not been quantified. However, Bortleson et al. (1980) documented substantial wetland loss surrounding 11 major river deltas, primarily due to placement of dikes and fill. GIS mapping and field observations have often documented the filling of historic coastal wetlands and pocket estuaries throughout Puget Sound (Johannessen et al. 2005, Johannessen and MacLennan 2006). Artificial fill areas are often at depositional beaches and/or drift cell termini and may not cause additional physical impacts to the net shore-drift system, though the ecological value of the filled site is typically degraded or largely eliminated. In some cases, where fill areas protrude waterward, net shore-drift can be impeded. WDNR's Shorezone database reports more than 211 miles of fill areas within Puget Sound and Northern Straits (2001).

Dredging for boat and ship access has also dramatically altered the nearshore in many parts of the Puget Lowland. Not just limited to urban bays and marina development, dredging has occurred throughout the region, often in formerly high-value estuarine areas such as Bridgehaven and Driftwood Key in Hood Canal (Hirschi et al. 2003), Lagoon Point and Sandy Hook on Whidbey Island, and Sandy Point, Whatcom County. Marinas in the main basin of Puget Sound were more typically built into deeper water, with less extensive dredging.

The Burlington Northern Santa Fe (BNSF) railroad has affected coastal geomorphic processes in several other Puget Sound areas where a causeway crossing a bay reduced tidal flushing. This is the case in Whatcom County's Mud/Chuckanut Bay and Padden Creek estuary, Skagit County's Fidalgo Bay, Pierce County's Chamber's Bay, and the southwest shore of Jefferson County's Discovery Bay. Decreased tidal flushing results in slowed water velocity, causing fine particles to settle out of suspension. This often accelerates local sedimentation rates, the long-term effects of which can permanently alter the surface-water hydrology of the bay(s) and eliminate submerged aquatic habitats. Reduced tidal flushing combined with accelerated sedimentation can also degrade water quality.

Shore Modifications

Shore modifications, almost without exception, impact the ecological functioning of nearshore coastal systems. The proliferation of these structures has been viewed as one of the greatest threats to the ecological functioning of coastal systems (PSAT 2003, Thom et al. 1994). Modifications often result in the loss of the very feature that attracted coastal property owners in the first place, the beach (Fletcher et al. 1997). Research on the impact of bulkheads on beaches is far from complete, and there is still disagreement in the literature (for example, Pilkey and Wright 1988, Kraus and McDougal 1996). There has been a great paucity of local bulkhead-related research in the region. The greatest need is for efforts that span at least five years of quantitative data collection.

A bulkhead constructed at or below OHWM results in the coarsening of beach sediment in front of the bulkhead (MacDonald et al. 1994, Kraus 1988). Fine-grain sediment is mobilized by increased turbulence caused by the bulkhead (Miles et al. 2001) and is preferentially transported away, decreasing the volume of beach sediment and leaving

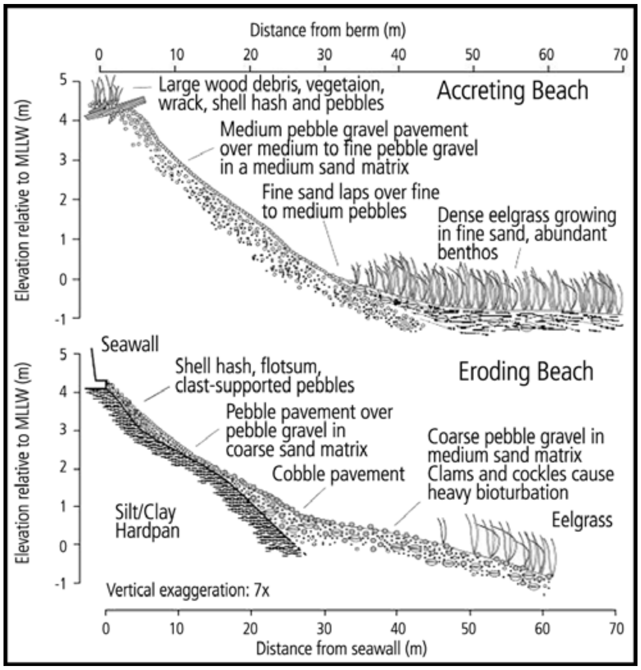


Figure 16. Beach profiles at nearby unmodified and accreting beach and bulkheaded eroding beach, with changes in substrate (Finlayson 2006).

only the coarse material behind (Figure 16). This can reduce the potential spawning areas for surf smelt and sand lance, which are of particular value to Pacific salmon as forage fish (Thom et al. 1994). These fish spawn in the upper intertidal portion of fine gravel and sand beaches, with a high percentage of 1-7 mm sediment (Pentilla 1978). Sand lance require 0.5-3.0 mm sediment for spawning. Beach sediment coarsening (resulting from shore modifications) can decrease or eliminate this valuable spawning habitat, as well as hardshell clam habitat.

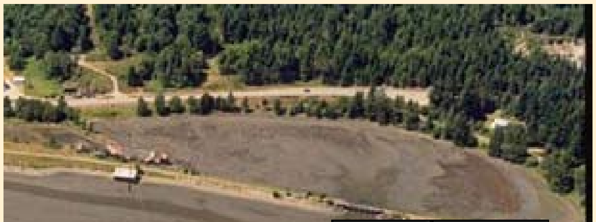
The installation of shore modifications typically results in the direct burial of the backshore area and portions of the beachface, resulting in reduced beach width (Griggs 2005) and loss of habitat area. Large woody debris (LWD) is usually lost from the beach following installation of bulkheads, with corresponding changes in habitat.

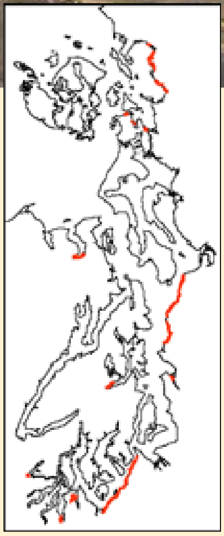
A recent study by Rice (2006) documented the effects of shoreline modifications on a Puget Sound beach on surf smelt mortality. Anthropogenic alteration of the shoreline typically makes beaches less suitable for surf smelt embryo survival, compared to unmodified shores. The loss of shade caused by removing riparian vegetation exposed beaches to greater sun, and thus increased temperature extremes and variation in the physical environment (Pentilla 2007).

Loss of marine riparian areas, vegetated bluffs and shores and their ecosystem functions are commonly associated with shoreline development and anthropogenically-modified shores. Functions occurring in unmodified marine riparian areas include water quality/pollution abatement, soil and slope stability, sediment control, wildlife habitat, microclimate control, shade, nutrient inputs, fish prey production and habitat structure/LWD (Brennan and Culverwell 2004). These functions are not just beneficial to humans, fish and wildlife, but to the health and integrity of nearshore marine ecosystems.

Burlington Northern Santa Fe Railway

A very apparent modification along the shores of several Puget Sound counties is the Burlington Northern Santa Fe (BNSF) Railway. The train tracks and associated revetment follow the shore for approximately 70.7 miles (WDNR 2001). Considerable lengths of eroding bluff (sediment sources) are impounded behind the rail revetment, which is wider, higher and extends farther onto the beach than residential shore modifications. The BNSF revetment also buried foreshore and backshore habitats, precludes the formation of depositional features, and interrupts shoreline connectivity. In addition, the revetment eliminates the marine riparian ecotone and the possibility of shade from overhanging vegetation, large woody debris recruitment, wildlife use and other terrestrial inputs into the marine ecosystem. The cumulative loss of sediment to Puget Sound and the Northern Straits net shore-drift systems is substantial and widespread. Further research is recommended to quantify and address he magnitude of the impacts associated with the BNSF revetments and causeways.





Above, South Discovery Bay, Jefferson County. Tidal restriction resulting from rail causeway. Right, Puget Sound and Northern Straits shores with railway revetments/ causeways (red). (WDNR 2001).

More readable color versions of this and all other graphics in this series are available at *www.pugetsoundnearshore.org/*.

Nearshore habitat assessments in the Puget Sound region have found that large estuaries and small "pocket" estuaries provide very high value nearshore habitat for salmon as well as other species (Beamer et al. 2003, Redman and Fresh 2005). Reduction in net shore-drift volumes due to bulkheading and other modifications, and site-specific impacts induced by modifications, can cause partial or major loss of the depositional landforms, such as spits that form estuaries and embayments. The reduction in beach sediment supply can also lead to an increase in coastal flooding and wave-induced damage to low elevation armoring structures and homes (Johannessen et al. 2005). Therefore, with consideration of all these factors, shore modifications can have substantial negative impacts on nearshore habitats.

Sand Rights

Coastal engineers and scientists have found that a significant percentage of coastal erosion is caused by the works of man, including dams, mining of coastal sand, urbanization, and coastal structures that block or divert sand from the beach system (Stone et al. 2005). Emerging questions of legal rights and liabilities have created a growing body of law, management and engineering work involving beach erosion, and property rights of landowners in the coastal zone. From these questions evolved the concept of "Sand Rights", which integrates legal, regulatory, economic and engineering principles to address these issues of beach management and enhancement (Stone et al. 2005).

Sand rights merge the physical laws of sediment transport with societal laws of public trust. The basic doctrine is that human actions will not interfere, diminish, modify or impede sand and other sediment from being transported to and along beaches, rivers and any other flowing or wind-blown path, without proper restitution. This doctrine requires that all decision makers give careful consideration to proposed or existing projects that interfere with the delivery or transport of sediment along the beach. To do so, projects should be designed to avoid any interference that the project may have with sand transport, or provide appropriate mitigation (Stone et al. 2005). For example, if a jetty is required to protect a major harbor entrance, the impacts to sediment transport caused by the jetty would need to be mitigated with regular sediment bypassing and/or beach nourishment.

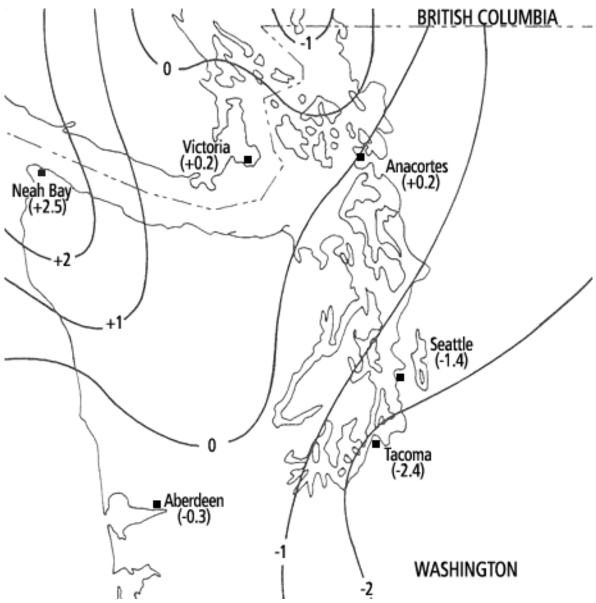


Figure 17. Contours of vertical land movement (millimeters per year) in coastal Washington (Shipman 1989). Positive values denote uplift, negative values denote subsidence.

Sea Level Rise and Global Climate Change

Over the past century, rapid coastal development has occurred throughout the Puget Sound region resulting in exponentially increasing total values of beachfront real estate, infrastructure and buildings. Unfortunately, this phenomenon has coincided with a century of accelerating global sea level rise (SLR) (Pilkey and Cooper 2004). A rise in sea level results in the landward migration of the sea, bringing shorelines closer to homes and infrastructure. These processes will have direct effects on the physical processes at work along Puget Sound and Northern Straits beaches and bluffs and the habitats found therein. Wise management of these shores will be more necessary than ever to protect nearshore ecosystems that depend on functioning nearshore processes, and to prevent loss of human life, property and infrastructure.

The Intergovernmental Panel on Climate Change's (IPCC 2001) Third Assessment suggested a rise of 0.09 to 0.88 meters by the year 2100 unless greenhouse gas emissions are reduced substantially. However, recent research warns that more rapid rises in sea level (greater than one meter per century) could occur given accelerated melting of the Greenland ice sheet and/or collapse of the West Antarctic ice sheet (Overpeck et al. 2006). Projections made regarding the ice melt have a high degree of uncertainty, and should be used cautiously. Updated projections of SLR that account for ice melt are a focus of much current research.

Sea level rise in the Puget Sound region departs from global-mean trends due to regional variations in oceanic-level change and vertical land movement. Upward land movement (uplift) offsets sea level rise, while downward movement (subsidence) increases SLR. As a result, the spatial variability of Puget Sound tectonics produces different rates of sea level rise across the region, referred to as relative sea level rise. The land is subsiding in much of Puget Sound, with rates ranging from zero in the eastern Strait of Juan de Fuca and north Puget Sound to more than 3 mm/yr in south Puget Sound near Tacoma (Figure 17, Shipman 1989). Thus, net local sea level rise is close to the global average in north Puget Sound, and is up to double the average in south Puget Sound (Snover et al. 2005).

Effects of SLR

It is well known that SLR will alter the current geomorphologic configuration of beaches and bluffs, thereby displacing ecosystems and increasing the vulnerability of infrastructure (IPCC 2001, Pethick 2001). However, no research has focused on the physical implications of sea level rise and global climate change on the coast of the Puget Lowland. Utilizing recent research conducted in similar environs can aid resource managers and policy makers to deduce the potential effects of SLR on Puget Sound geomorphologic processes.

The major physical impacts resulting from a rise in sea level include erosion of beaches and bluffs, landward migration (translation) of barrier beaches, inundation of low-lying areas (particularly deltas), flooding, and loss of many marshes and wetlands. Additionally, increased precipitation, storm frequency and intensity, as well as changes in the paths of storms are also likely to considerably increase storm damage in the region as a result of increased oceanic temperatures (IPCC 2001, Neumann et al. 2000).

Recent research has reported that bluffs composed of glacial deposits, which make up most of the region's bluffs, are likely to retreat more rapidly in the future due to increased toe erosion resulting from sea-level rise (Bray and Hooke 1997). In formerly glaciated bays of eastern Canada, researchers have already made the link between the rate of relative sea level rise and increased sediment supply from coastal bluffs (IPCC 2001). Bluff recession rates are also expected to increase in many areas due to increased precipitation, storminess (wave energy) and storm frequency, and higher groundwater levels (Hosking and McInnes 2002, Pierre and Lahousse 2006). Lower bank shores are expected to reach equilibrium more quickly than higher banks and bluffs (Bray and Hooke 1997), though SLR is expected to continue for centuries. It is likely that erosion rates will increase less in areas with lower wave energy (Emery and Kuhn 1982), such as south Puget Sound, compared to areas of higher (relative) wave energy, such as the Northern Straits.

In addition to increased erosion rates, shores that are currently stable are expected to begin to erode and those accreting should stabilize, though local sediment supply and other site-specific conditions will influence how each shore responds to SLR (IPCC 2001). Bray and Hooke (1997) suggest that bluffs with a history of landslides will be more susceptible to further failures, especially in locations where bluff recession intersects ancient landslides. Reactivation of these forms, such as the deep-seated slide areas of west Whidbey Island, Termination Point in Eastern Jefferson County, or Sunrise Beach in Thurston County, will result in greater instability and retreat than would otherwise be anticipated.

Changes in sea level will also result in a spatial response of beach profiles, with landward and upwards translation of the beach, in a concept known as the Bruun rule (1962). This basic idea (though its accurate application to individual beaches is not well understood) appears to apply to all coastal landforms (Pethick 2001). The landward migration of the shoreline is a response to the changes in the elevation of breaking waves on the beach profile, brought about by SLR. This response is generally a self-regulating process, as additional (eroded) sediment from the backshore or bluffs allows for down-drift shores to translate landward, thereby maintaining profile morphology (Bray and Hooke 1997). The effects of SLR and the Bruun rule are likely to be most visually evident along low-elevation shores, including salt marshes and barrier beaches/spits. The filled mudflats that encompass the region's major ports, including Elliot Bay, Commencement Bay, the shoreline from Mukilteo to Everett, and Olympia's Port Peninsula, are likely to be threatened with inundation (Canning 2001).

Beaches and bluffs currently armored are expected to have increased water depths and be subject to greater wave energy, storm run-up, beach loss, and probability of structural damage, requiring construction to repair and improve structures (Bray and Hooke 1997). Soft shore protection strategies are recommended for mitigating sea level rise, as hard protection does not respond to the fundamental problem of diminishing sediment sources (Neumann et al. 2000).

Additional implications of global climate change result from warmer ocean conditions, including more frequent and greater magnitude storm events, increased precipitation, and more frequent and longer lasting El Niño(s). SLR due to El Niño often results in increased frequency and magnitude of coastal erosion, increased precipitation and storm surge flood events (Canning 2001). Allen and Komar (2002) have documented a progressive increase in winter wave heights and periods in the Pacific Ocean off the coast of Washington and Oregon over the past 25 years. This suggests that increases in wave energy may also be attributed to global climate change.

Management Implications

In most cases, the impacts of SLR can be mitigated by forward-looking state or local land-use policies. A major obstacle that must be overcome includes improving our integration of these concepts into Puget Sound socio-economic and environmental context, as well as the accessibility and application of the science by state and local decision-makers who are most able to prepare coastal areas to respond to the threat of sea level rise (Neumann et al. 2000).

Knowing that shoreline translation (landward movement of shore features) is to occur offers resource managers a tool, allowing decisions to be made to accommodate and, where possible, facilitate such migration (Pethick 2001, Nordstrom 2000). Management responses include moving houses and infrastructure landward. Additional setback distances and buffers will be required for new construction atop regional bluffs and no-bank shores as erosion rates accelerate, as well as to accommodate shoreline translation. Accommodating shoreline translation can enable salt marshes, sand dunes and beaches to transgress (move landwards while maintaining their overall form). This concept is commonly referred to as "managed retreat" or "managed realignment" (Cooper 2003). Additionally, policies that limit reconstruction and prohibit rebuilding in high-risk areas should be employed (Neumann et al. 2000).

Another appropriate management response is to prohibit the installation of shoreline armoring (bulkheads or riprap). In areas with narrow setback distances, there will likely be increased pressure to install emergency erosion control structures (due to increased erosion rates, storminess and storm frequency). However, shoreline armoring prevents shoreline translation by impounding nearshore sediment, which leads to habitat loss in a process referred to as the "coastal squeeze," and does not provide a long-term solution to the erosion brought about by SLR, which is expected to occur for centuries. Coastal squeeze refers to the loss of beach that occurs as a result of a bulkheaded or otherwise armored shore and a rising sea level (IPCC 2001). In addition, many erosion control structures are engineered for historic conditions and will not curb anticipated erosion rates under SLR scenarios (Emery and Kuhn 1982). Erosion control measures should be restricted to beach nourishment and soft shore protection, a method that does not impede natural coastal geomorphic processes.

Puget Sound and Northern Straits beaches will undoubtedly incur considerable habitat loss, unless managers aggressively employ pro-active approaches and start initiating programs focused on accommodating sea level rise and utilizing strategies such as managed retreat.

Coastal Restoration

Restoring and improving the functions of the physical processes along Puget Sound area beaches and bluffs is essential to preserving and restoring nearshore habitats, and needs to occur on many levels. These include, in order of increasing costs, enforcing existing regulations more fully, carrying out conservation/preservation efforts at functioning sites, and conducting coastal restoration. This will involve removing bulkheads, jetties and fill areas that impair net shore-drift, carrying out sediment bypass operations at drift obstructions, restoring stream flow and estuarine conditions, and nourishing beaches. An essential element to enacting restoration and conservation is to engage the public in education and to try to get its participation and stakeholder buy-in (Simenstad et al. 2005). Ways to do this include better outreach, and installing coastal restoration projects in public places to serve as demonstration projects.

A restoration conceptual model for beaches and bluffs was developed as part of this Valued Ecosystem Component effort. The model was developed by the authors of this paper with input from members of the Nearshore Science Team of the Puget Sound Nearshore Partnership. The model links proposed restoration actions (management measures) to restored natural processes, structural changes and functional responses (Figure 18). The model focuses on restoration of physical processes in order to improve the functioning of natural processes and habitats. For example, removing littoral drift (net shore-drift) barriers would increase coastal sediment transport, which would in turn effect a number of structural changes such as beach substrate size, increase in backshore area, and a change in mass wasting. The functional response to these structural changes would be a more fully functioning drift cell and increased habitat complexity and area, which would in turn have influences on species that use the nearshore (Figure 18).

The goal of the conceptual model is to illustrate process-based restoration actions that will have lasting habitat benefits over time. Sustainable restoration efforts restore processes, not just specific elements or site characteristics that cannot be replenished naturally. An example of a sustainable restoration action is to restore sediment input to the nearshore by removing bulkheads at historic feeder bluff sites, thereby allowing gradual and ongoing erosion/mass wasting of bluffs and LWD recruitment, instead of one-time beach nourishment. A rare example of bulkhead removal at a feeder bluff prioritized for restoration (Johannessen et al. 2005) is under way in the City of Normandy Park (Johannessen et al. 2006). Structural changes thought to result from bulkhead removal at feeder bluff sites outlined in the model also include increased intertidal and backshore area (Figure 18). The anticipated functional responses of this action include increased habitat complexity and area. Other Valued Ecosystem Component models also tie into the above model, such as the changes in coastal forest dynamics and forage-fish habitat with restoration of bluff sediment input to beaches.

Coastal projects intended to improve the functioning of sites fall into several categories: coastal restoration, coastal enhancement/rehabilitation, and soft shore protection. Coastal restoration refers to true restoration, back to close-to-original conditions. These projects have been dominated by dike breaching and flooding of historic estuarine areas, with a few sites of stream mouth and barrier beach restoration. Examples of dike breaching have occurred in the Skagit, Snohomish, and Nisqually river deltas. Numerous small estuarine rehabilitation efforts have taken place along with cleanup of contaminated sites in the Duwamish River estuary (Simenstad et al. 2005). Examples of stream mouth restoration include Jimmycomelately Creek in Sequim Bay. A limited number of open beach restoration projects have occurred also, such as at Driftwood Beach in San Juan County (see sidebar). Another recent example of a beach restoration project was at Seahurst Park in Burien. The failing bulkhead at the southern third of the mile-long park shore was removed in 2004 and replaced with a recreated gravel and sand beach, with extensive backshore planting and reconnection of historic feeder bluff with the Sound (Hummel et al. 2005).

Coastal enhancement or rehabilitation refers to improving conditions in impaired systems that will likely require long-term management (Simenstad et al. 2005). Beach projects aimed at removing coastal structures or fill and enhancing conditions at estuaries or on open coasts have almost always been compromises between preserving human uses of the backshore or uplands and true restoration. An example of enhancement occurred at the mouth of the Chimacum Creek estuary in eastern Jefferson County (Figure 19). The Chimacum project, like most, was a compromise between true coastal restoration and preserving and protecting some amount of upland fill.

Beach enhancement/rehabilitation projects on open coasts have been referred to as soft shore protection (Johannessen 2002). Gravel beach nourishment has been one of the primary tools for soft shore protection projects in the region, along with anchored large woody debris, planting and sometimes small structural elements. Residential examples are outlined in Zelo et al. (2000), and the Puget Sound Action Team (PSAT) has recently published a qualitative study of the success of many of the projects outlined in the paper by Zelo et al. (Gerstel and Brown 2006).

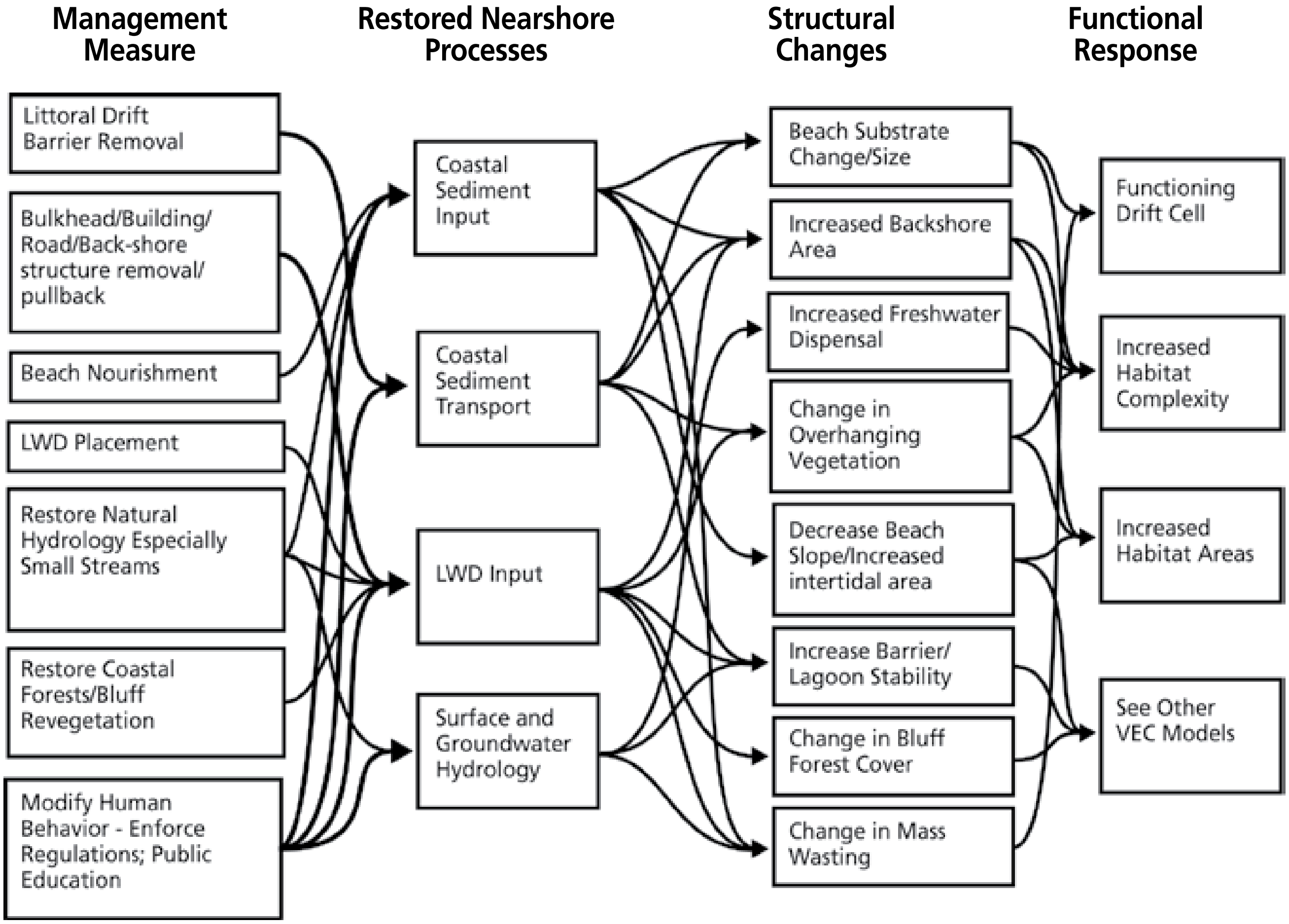


Figure 18. Restoration conceptual model for beaches and bluffs developed for this paper. Bold indicates greater assumed importance.

Many Seattle and King County parks have soft shore protection projects, typically including gravel nourishment (such as Golden Gardens, Lincoln Park, Discovery Park, and Cormorant Cove, Shipman 2002). Public parks are well suited to nourishment projects due to their long shorelines, high value placed on beaches by park planners, and ability of decision makers to experiment (Shipman 2002). Although beach monitoring exists for some sites, it has been underutilized to date due to permit requirements. Most of these beach projects were poorly documented with very limited follow-up monitoring (even the recent Seahurst project missed early monitoring milestones); this represents a data gap in understanding the response of beaches and surrounding habitats.

Prime areas for far-reaching, cost effective coastal restoration exist in rural areas of the region. Examples of potential large projects are removing/modifying blocking dikes and roadways from the many former salt marshes isolated by Highway 101 in Hood Canal and the Lummi River estuary. Many small estuarine and coastal projects have recently been identified in San Juan County (Johannessen and MacLennan 2006). The Puget Sound Nearshore Partnership, the Shared Strategy for Puget Sound, and the Alliance for Puget Sound have all recently established lists of coastal restoration projects for implementation.

Figure 19. Coastal restoration immediately south of Chimacum Creek mouth, eastern Jefferson County (Hugh Shipman). Large woody debris was placed on the waterward edge of a reduced fill area.

Driftwood Beach Restoration – The Driftwood Beach project was designed and constructed for the Blakely Island Maintenance Commission, which is the community group composed of the majority of Blakely Island, San Juan County, property owners. The beach had been mined for gravel and was rapidly eroding as fill was exposed to waves. The project involved re-creating a 600-ft long protective gravel berm to restore and protect the eroding narrow upland access area. Backshore restoration involved removing fill and debris and importing sand, with extensive planting using locally collected native plants and seeds. Soil fill and debris were first removed from the upper berm and backshore area. The beach was constructed in February and early March 1999 (Johannessen 2002). Five years of beach monitoring data from Driftwood Beach revealed that the beach within the nourishment area has essentially been stable since installation. Beach profile changes were generally restricted to 0.3 feet of vertical change. Minor onshore transport of gravel occurred as the berm moved landward and increased in elevation. The protective berm-beach performed very well through the summer of 2006. The project achieved all pre-project goals: protect the small community-owned beach area, restore the backshore to a natural condition with a native plant community, and have no waterward movement of nourishment gravel, thus protecting eelgrass and macroalgae.

before

after

References

Allen, J.C. and P.D. Komar, 2002. Extreme storms on the PNW coast during the 1997-98 El Nino and 1998-99 La Nina. Journal of Coastal Research 18(1):175-193.

Bauer, W. 1976. The drift sectors of Whatcom County marine shores: Their shoreforms and geo-hydraulic status. Whatcom County Planning Commission, 74 p., 1 map.

Beamer, E., R. Henderson, A. McBride, and K. Wolf. 2003. The importance of non-natal pocket estuaries in Skagit Bay to wild Chinook salmon: an emerging priority for restoration. Skagit System Cooperative, Research Department. La Conner, Washington, 10 p.

Bird, E. 2000. Coastal Geomorphology, an Introduction. John Wiley and Sons, Ltd. Chichester, England, 340 p.

Bird, E. 2005. Appendix 5: Glossary of coastal geomorphology. Pages 1155-1192 *in* M. L. Schwartz (ed.). Encyclopedia of Coastal Science. Springer. Dordrecht, The Netherlands.

Bishop, D.M. and M.E. Stevens. 1964. Landslides on logged areas in Southeast Alaska. USDA Forest Service Research Paper. NOR-1, 18 p.

Booth, D.B. 1991. Geologic map of Vashon and Maury Islands, King County, Washington. USGS Miscellaneous Field Studies. Map MF-2161.

Booth, D.B. 1994. Glaciofluvial infilling and scour of the Puget Lowland, Washington, during ice-sheet glaciation. Geology 22:695-698.

Bortleson, G.C., M.S. Chrzastowski, and A.K. Helgerson. 1980. Historic changes of shoreline and wetlands at eleven major deltas in the Puget Sound region, Washington. Atlas HA-617. Department of the Interior, US Geological Survey.

Bray, M.J. and J.M. Hooke. 1997. Prediction of soft-cliff retreat with accelerating sea level rise, Journal of Coastal Research 13(2):453-467.

Brennan, J.S. 2007. Marine Riparian Vegetation Communities of Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-02. Published by Seattle District, U.S. Army Corps of Engineers. Seattle, Washington. Available online: *www.pugetsoundnearshore.org.*

Brennan, J.S. and H. Culverwell. 2004. Marine Riparian: An assessment of riparian functions in marine ecosystems. Published by Washington Sea Grant. Copyright 2005. University of Washington Board of Regents, Seattle, WA. 27 p.

Brunsden, D. 2001. A critical assessment of the sensitivity concept in geomorphology. Catena (42):99-123.

Bruun, P. 1962. Sea-level rise as a cause of shore erosion. Journal Waterways and Harbors Division 88(1-3):117-130.

Buchannan, J.B. 2006. Nearshore Birds in Puget Sound. Puget Sound. Puget Sound Nearshore Partnership Report No. 2006-05. Published by Seattle District, U.S. Army Corps of Engineers. Seattle, Washington. Available online: *www.pugetsoundnearshore.org*

Canning, D.J. 2001. Climate variability, climate change, and sea-level rise in Puget Sound: Possibilities for the future. Proceedings of Puget Sound Georgia Basin Research Conference 2001. 9 p.

Chu, Y.H. 1985. Beach erosion and protection: a case study at Lincoln Park, Seattle. Shore and Beach (53):26-32.

Cooper, N.J. 2003. The use of 'managed retreat' in coastal engineering. Engineering Sustainability 156, June 2003(ES2):101-110.

Davis, R.A. Jr. 2005. Human impacts on coasts. Pages 530-535 *in* M. L. Schwartz (ed.). Encyclopedia of Coastal Science.

Dethier, M.N. 2006. Native Shellfish in Nearshore Ecosystems of Puget Sound. Puget Sound Nearshore Partnership Report No. 2006-04. Published by Seattle District, U.S. Army Corps of Engineers. Seattle, Washington. Available online: *www.pugetsoundnearshore.org*

Downing, J. 1983. The Coast of Puget Sound: Its Processes and Development. University of Washington Press, Seattle, 126 p.

Easterbrook, D.J. 1976. Map showing engineering characteristics of geologic materials, western Whatcom County, Washington. U.S. Geological Survey Miscellaneous Investigations Series Map I-854-D, 1 sheet, scale 1:62,500.

Easterbrook, D.J. 1992. Advance and retreat of the Cordilleran ice sheets in Washington, U.S.A. Geographie Physique et Quaternaire 46(1):51-68.

Eissinger, A. 2007. Great blue heron in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-06. Published by Seattle District, U.S. Army Corps of Engineers. Seattle, Washington. Available online: *www.pugetsoundnearshore.org.*

Emery, K.O. and G.G. Kuhn. 1982. Sea cliffs: Their processes, profiles, and classification. Geological Society of America Bulletin (93):644-654.

Finlayson, D.P. 2006. The geomorphology of Puget Sound beaches. Dissertation, School of Oceanography, University of Washington. Seattle, WA, 216 p.

Finlayson, D.P. and H. Shipman. 2003. Puget Sound drift cells: the importance of waves and wave climate. Puget Sound Notes. Olympia, WA. p. 1-4.

Fletcher, C.H., R.A. Mullane and B.M. Richmond. 1997. Beach loss along armored shorelines on Oahu, Hawaiian Islands. Journal of Coastal Research 13(1):209-215.

Fresh, K.L. 2006. Juvenile Pacific Salmon in Puget Sound. Puget Sound Nearshore Partnership Report No. 2006-06. Published by Seattle District, U.S. Army Corps of Engineers. Seattle, Washington. Available online: *www.pugetsoundnearshore.org*

Gerstel, W.J. and J.F. Brown. 2006. Alternative shoreline stabilization evaluation project. Prepared for the Puget Sound Action Team, 43 p.

Gerstel, W.J., M.J. Brunengo, W.S. Lingley Jr., R.L. Logan, H.S. Shipman and T.J. Walsh. 1997. Puget Sound bluffs: the where, why, and when of landslides following the holiday 1996/97 storms. Washington Geology. March 1997, 25(1):17-31.

Gray, D., and R.B. Sotir. 1996. Biotechnical and soil bioengineering slope stabilization: A practical guide for erosion control. John Wiley and Sons, 378 p.

Griggs, G.B., 2005. The impacts of coastal armoring. Shore and Beach 73(1):13-22.

Griggs, G.B. and J.F. Tait. 1990. Beach response to the presence of a seawall: a comparison of field observations. Shore and Beach 58:11-28.

Griggs, G.B., J.F. Tait and W. Corona. 1994. The interaction of seawalls and beaches: seven years of monitoring, Monterey Bay, California. Shore and Beach 63(2):31-36.

Herrera Environmental Consultants, Inc. 2005. Marine shoreline sediment survey and assessment: Thurston County, Washington. Prepared for Thurston Regional Planning Council. Olympia, WA.

Hirschi, R., T. Labbe, A. Carter-Mortimer. 2003. Shoreline alterations in Hood Canal and Eastern Strait of Juan de Fuca. Prepared for the Point No Point Treaty Council, Kingston, Washington. 62 p.

Hosking, A. and R. McInnes. 2002. Preparing for the impacts of climate change on the Central Southeast of England: a framework for future risk management. Journal of Coastal Research. Special Issue 36:381-389.

Hummel, P., S. Thomas, J. Dillon, J. Johannessen, P. Schlenger, and W. Laprade. 2005. Seahurst Park: restoring nearshore habitat and reconnecting natural sediment supply processes, in Puget Sound Georgia Basin Research Conference 2005, Session F7.

Intergovernmental Panel on Climate Change. 2001. Climate change 2001: impacts, adaptation, and vulnerability. J.J. McCarthy, O.F. Canziani, N.A. Leary, D.D. Dokken, K.S. White (eds.). Available online: *www.grida.no/climate/ipcc_tar/wg2/index.htm.*

Jackson, N.L. and K.F. Nordstrom. 1992. Site specific controls on wind and wave processes and beach mobility on estuarine beaches in New Jersey, U.S.A. Journal of Coastal Research 8(1):88-97.

Jacobsen, E.E. and M.L. Schwartz. 1981. The use of geomorphic indicators to determine the direction of net shore-drift. Shore and Beach 49:38-42.

Johannessen, J.W. 1992. Net shore-drift in San Juan County and parts of Jefferson, Island, and Snohomish counties, Washington: final report. Western Washington University, for Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia, 58 p., 25 maps.

Johannessen, J.W. 1999. Critical shoreline areas relative to critical nearshore habitats at Tala Point to Kala Point, eastern Jefferson County, WA. Prepared for Jefferson County Planning Department. 27 p., 3 maps.

Johannessen, J.W., 2002. Soft shore protection as an alternative to bulkheads – projects and monitoring. Proceedings of Puget Sound Research 2001. Bellevue, WA. Puget Sound Action Team, Session 4b.

Johannessen, J.W. and M.A. Chase. 2003. Point Whitehorn to Birch Bay state park shoreline reach analysis, Whatcom County, WA-Final Report. Prepared for Whatcom County Public Works, River and Flood Division. 28 p., 5 appendices.

Johannessen, J.W. and M.A. Chase. 2005. Island County feeder bluff and accretion shoreform mapping. Prepared for Island County Marine Resource Committee. 33 p.

Johannessen, J.W. and A. MacLennan. 2006. Soft-shore protection/structure removal blueprint for San Juan County forage fish beaches. Prepared for Friends of the San Juans. 40 p.

Johannessen, J.W., A.J. MacLennan, and A. McBride. 2005. Inventory and assessment of current and historic beach feeding sources/erosion and accretion areas for the marine shorelines of Water Resource Areas 8 & 9. Prepared by Coastal Geologic Services, for King County Department of Natural Resources and Parks. Seattle, Washington. 80 p., 5 appendices.

Johannessen, J.W., A. MacLennan and J. Waggoner. 2006. Beaconsfield on the Sound bulkhead removal feasibility study. Prepared for Cascade Land Conservancy. 34 p.

Keuler, R.F. 1979. Coastal zone processes and geomorphology of Skagit County, Washington. Master's thesis, Western Washington University, Bellingham, WA. 123 p.

Keuler, R.F. 1988. Map showing coastal erosion, sediment supply, and longshore transport in the Port Townsend 30-by 60-minute quadrangle, Puget Sound region, Washington. U.S. Geologic Survey Miscellaneous Investigations Map I-1198-E, scale 1:100,000.

Kirk, R.M. 1980. Mixed sand and gravel beaches: morphology, processes and sediments. Progress in Physical Geography 4:189-210.

Komar, P.D. 1976. Beach processes and sedimentation. Englewood Cliffs, NJ. Prentice-Hall. 429 p.

Kraus, N.C. 1988. The effects of seawalls on the beach: An extended literature review. *In* N.C. Kraus and O.H. Pilkey (eds.). The Effects of Seawalls on the Beach. Journal of Coastal Research, Spec. Iss. 4:1-29.

Kraus, N.C. and W.G. McDougal. 1996. The effects of seawalls on the beach: part 1, an updated literature review. Journal of Coastal Research 12(3):691-701.

Lapen, T. 2000. Geologic Map of the Bellingham 1:100,000 Quadrangle, Washington. Open file report 2000-5, plate 1. Washington Division of Geology and Earth Resources, Washington Department of Natural Resources.

MacDonald, K., D. Simpson, B. Paulsen, J. Cox, and J. Gendron. 1994. Shoreline armoring effects on physical coastal processes in Puget Sound, Washington. Coastal Erosion Management Studies, vol. 5, Shorelands Program, Washington Deptartment of Ecology, Olympia, WA. DOE Report 94-78.

Marsh, W.M. 2005. Landscape Planning; environmental applications. John Wiley and Sons, Inc. 472 p.

Menashe, E. 1993. Vegetation management: A guide for Puget Sound bank property owners, shorelands and coastal zone management program. Washington Department of Ecology, Olympia, WA. Available online: *www.ecy.wa.gov/programs/sea/pubs/93-31/intro.html.*

Miles, J.R., P.E. Russell, and D.A. Huntley. 2001. Field measurements of sediment dynamics in front of a seawall, Journal of Coastal Research 17(1):195-206.

Montgomery, D.R., K.M. Schmidt, H. Greenberg, W.E. Dietrich. 2000. Forest clearing and regional landsliding. Geology 28:311-314.

Mumford, T.F. 2007. Kelp and Eelgrass in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-05. Published by Seattle District, U.S. Army Corps of Engineers. Seattle, Washington. Available online: *http://www.pugetsoundnearshore.org.*

National Oceanic and Atmospheric Administration (NOAA). 2006. Tides and currents website. Available online: *http://tidesandcurrents.noaa.gov/station_retrieve.shtml?type=Tide%20Data&state=Washington&id1=944*

Nightingale, B., and C. Simenstad. 2001. Executive summary – over-water structures: marine issues. White paper, prepared for Washington Department of Fish and Wildlife, Washington Department of Ecology, and Washington Department of Transportation, Olympia, WA. 181 p.

Neumann, J.E., G. Yohe, R. J. Nicholls and M. Manion. 2000. Sea-level rise and global climate change: a review of impacts to U.S. coasts. Arlington, Virginia. Pew Center on Global Climate Change. Available online: *www.pewclimate.org/global-warming-in-depth/all_reports/sea_level_rise/index.cfm.*

Nordstrom, K.F. 1992. Esturarine beaches. Elsevier, New York. 225 p.

Nordstrom, K.F. 2000. Beaches and Dunes of Developed Coasts. Cambridge University Press. Cambridge, UK.

Osterkamp, W.R. and R.A. Morton. 2005. Mining of Coastal Materials. Pages 530-535 *in* M. L. Schwartz (ed.). Encyclopedia of Coastal Science.

Overpeck, J.T., B.L. Otto-Bleisner, G.H. Miller, D.R. Muhs, R.B. Alley and J.T. Kiehl. 2006. Palaeoclimatic evidence for future ice-sheet instability and rapid sea level rise. Science 311:1747-1750.

Pentilla, D. 1978. Studies of surf smelt (*Hypomesus pretiosus*) in Puget Sound, Washington Department of Fisheries, Technical Report no. 42, 47 p.

Pentilla, D. 2007. Marine Forage Fishes in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-03. Published by Seattle District, U.S. Army Corps of Engineers. Seattle, Washington. Available online: *www.pugetsoundnearshore.org.*

Pethick, J. 2001. Coastal management and sea-level rise. Catena 42:307-322.

Pierre, G. and P. Lahousse. 2006. The role of groundwater in cliff instability: an example at Cape Blanc-Nez (Pas-de-Calais, France). Earth Surfaces Processes and Landforms. 31:31-45.

Pilkey, O.H. and J.A. Cooper. 2004. Society and sea level rise. Science 303:1781-1782.

Pilkey, O.H and H.L. Wright. 1988. Seawalls versus beaches. *In* N.C. Kraus and O.H. Pilkey (eds.). The Effects of Seawalls on the Beach. Journal of Coastal Research. Spec. Iss. 4:41-64.

Puget Sound Action Team (PSAT). 2003. 2003 Puget Sound update, Olympia, WA, 127 p.

Redman, S. and K. Fresh. 2005. Regional nearshore and marine aspects of salmon recovery. Puget Sound Action Team and NOAA Fisheries Olympia/Seattle, WA.

Rice, C.A. 2006. Effects of shoreline modification on a Northern Puget Sound beach: Microclimate and embryo mortality in surf smelt (*Hypomesus pretiosus*). Estuaries and Coasts 29(1):63-71.

Roering, J.J., K.M. Schmidt, J.D. Stock, W.E. Dietrich and D.R. Montgomery. 2003. Shallow landsliding, root reinforcement, and the spatial distribution of trees in the Oregon Cost Range. Canadian Geotechnical Journal 40:237-253.

Schmidt, K.M., J.R. Roering, J.D. Stock, W.E. Dietrich, D.R. Montgomery, and T. Schaub. 2001. Root cohesion variability and shallow landslide susceptibility in the Oregon Coast Range. Canadian Geotechnical Journal 38:995-1024.

Schwartz, M.L., et al. 1991. Net shore-drift in Washington State: Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia, WA.

Shannon and Wilson, Inc. 2000. Seattle landslide study. Prepared for Seattle Public Utilities, Seattle, WA.

Shipman, H. 2004. Coastal bluffs and sea cliffs on Puget Sound, Washington. *In* M.A. Hampton and G.B. Griggs (eds.). Formation, Evolution, and Stability of Coastal Cliffs—Status and Trends. 1693, U.S. Department of the Interior, U.S. Geological Survey, Denver, CO., 123 p.

Shipman, H. 2002. Beach nourishment on Puget Sound: a review of existing projects and potential applications. Pages 1-8 *in* Puget Sound Research 2001. Washington: Puget Sound Water Quality Action Team.

Shipman, H. 1989. Vertical land movements in coastal Washington: Implications for relative sea level changes. Technical Report PV-11, Shorelands and Coastal Zone Management, Washington Department of Ecology, Olympia, WA. 37 p.

Shipman, H. 1995. The rate and character of shoreline erosion on Puget Sound. Pages 77-83 *in* Puget Sound Water Quality Action Team, Puget Sound Research '95.

Shipman, H. 1998. Shoreline changes at North beach, Samish Island. Shorelands and Environmental Assistance program, Washington Department of Ecology. Publication 98-101. Olympia, WA.

Simenstad, C., C. Tanner, C. Crandell, J. White, and J. Cordell. 2005. Challenges of habitat restoration in a heavily urbanized estuary: evaluating investment. Journal of Coastal Research Spec. Iss. 40:6-23.

Snover, A.K., P.W. Mote, L. Whitely Binder, A.F. Hamlet, and N.J. Mantua. 2005. Uncertain future: climate change and its effects on Puget Sound. A report for the Puget Sound Action Team by the Climate Impacts Group (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle.

Stone, K., O. Magoon, B. Edge and L. Ewing. 2005. Sand rights. *In* M.L. Schwartz (ed.). Encyclopedia of Coastal Science. Springer. Dordrecht, The Netherlands, 1211 p.

Tait, J.F. and G.B. Griggs. 1991. Beach response to the presence of a seawall: a comparison of field observations. U.S. Army Corps of Engineers Waterways Experiment Station, Contract Report CERC 91-1, 60.

Thom, R.M., D.K. Shreffler, and K. MacDonald. 1994. Shoreline armoring effects on coastal ecology and biological resources in Puget Sound, Washington. Coastal Erosion Management Studies, Volume 7. Shorelands and Water Resources Program, Washington Department of Ecology, Olympia, WA.

Thorson, G.W. 1987. Soil bluffs + rain = slide hazards. Washington Geologic Newsletter 15:3-11.

Tubbs, D.W. 1974. Landslides in Seattle, Washington. Division of Geology and Earth Resources Information Circular 52, 15 p., 1 plate.

Uda, T. 2005. Spits. Pages 909-912 *in* M.L. Schwartz (ed.). Encyclopedia of Coastal Science Springer. Dordrecht, The Netherlands, 1211 p.

Wallace, R.S. 1988. Quantification of net shore-drift in Puget Sound and the Strait of Juan de Fuca, Washington. Journal of Coastal Research 4:395-403.

Washington State Department of Natural Resources (WDNR). 2001. Washington State ShoreZone Inventory, Nearshore Habitat Program, Olympia, WA.

Washington State Department of Natural Resources (WDNR) – Division of Geology and Earth Resources. 2001. Digital geologic maps of the 1:100,000 quadrangles of Washington. Olympia, Washington. Available online: *www.dnr.wa.gov/geology/dig100k.htm.*

Washington State Department of Ecology (WDOE). 1978-1980. Washington State Coastal Zone Atlas (12 volumes). Washington Shorelands and Coastal Zone Management Program.

Zelo, I., H. Shipman, and J. Brennan. 2000. Alternative bank protection methods for Puget Sound shorelines, prepared of the Shorelands and Environmental Assistance Program, Washington Department of Ecology, Olympia, WA, Pub. no. 00-06-012.

Zenkovich, V.P. 1967. Processes of Coastal Development. Oliver and Boyd.

PSNERP and the Nearshore Partnership

The **Puget Sound Nearshore Ecosystem Restoration Project** (PSNERP) was formally initiated as a General Investigation (GI) Feasibility Study in September 2001 through a cost-share agreement between the U.S. Army Corps of Engineers and the State of Washington, represented by the Washington Department of Fish and Wildlife. This agreement describes our joint interests and responsibilities to complete a feasibility study to "… *evaluate significant ecosystem degradation in the Puget Sound Basin; to formulate, evaluate, and screen potential solutions to these problems; and to recommend a series of actions and projects that have a federal interest and are supported by a local entity willing to provide the necessary items of local cooperation.*"

Since that time, PSNERP has attracted considerable attention and support from a diverse group of individuals and organizations interested and involved in improving the health of Puget Sound nearshore ecosystems and the biological, cultural, and economic resources they support. The **Puget Sound Nearshore Partnership** is the name we have chosen to describe this growing and diverse group and the work we will collectively undertake, which ultimately supports the goals of PSNERP but is beyond the scope of the GI Study. We understand that the mission of PSNERP remains at the core of the Nearshore Partnership. However, restoration projects, information transfer, scientific studies and other activities can and should occur to advance our understanding and, ultimately, the health of the Puget Sound nearshore beyond the original focus and scope of the ongoing GI Study. As of the date of publication for this Technical Report, the Nearshore Partnership enjoys support and participation from the following entities:

- King Conservation District
- King County
- Lead Entities
- National Wildlife Federation
- NOAA Fisheries
- Northwest Indian Fisheries Commission
- Northwest Straits Commission
- People for Puget Sound
- Pierce County
- Puget Sound Partnership
- Recreation and Conservation Office
- Salmon Recovery Funding Board
- Taylor Shellfish Company
- The Nature Conservancy
- U.S. Army Corps of Engineers
- U.S. Department of Energy – Pacific Northwest National Laboratory
- U.S. Environmental Protection Agency
- U.S. Geological Survey
- U.S. Fish and Wildlife Service
- U.S. Navy
- University of Washington
- Washington Department of Ecology
- Washington Department of Fish and Wildlife
- Washington Department of Natural Resources
- Washington Public Ports Association
- Washington Sea Grant
- WRIA 9

Information about the Nearshore Partnership, including the PSNERP work plan, technical reports, the Estuary and Salmon Restoration Program, and other activities, can be found on our Web site at: *www.pugetsoundnearshore.org*.

Document produced by Washington Sea Grant

PUGET SOUND
NEARSHORE
PARTNERSHIP

RESTORING OUR
ECOSYSTEM HEALTH

Puget Sound Nearshore Partnership/
Puget Sound Nearshore Ecosystem Restoration Project

c/o Washington Department of Fish and Wildlife

Mailing Address: 600 Capitol Way North,
Olympia, Washington 98501-1091

Contact: *pugetsoundnearshore@dfw.wa.gov*
or vist our website at: *www.pugetsoundnearshore.org*